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Transport Canada Multi Tank Car Impact Tests and Analysis

Report 1: Yard Impact Testing

Prepared for
Transportation Development Centre
Safety and Security
Transport Canada

by

Centre for Surface Transportation Technology
National Research Council Canada
Ottawa

March 1998

Canada

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Xiaohua Tong and Renguang Dong
Centre for Surface Transportation Technology
National Research Council Canada
Ottawa

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This report reflects the views of the authors and not necessarily those of the Transportation Development Centre.

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16. Abstract

This report describes the results of a series of yard impact tests on railway tank cars. The tests were conducted at the impact test facility of the Centre for Surface Transportation Technology, National Research Council Canada. Eight stub sill tank cars were used in the tests. The maximum number of hammer (moving) tank cars was three and the maximum number of anvil (stationary) tank cars was five. Fifteen different cases were tested to cover most of the situations that would occur in the practical operations of a railway switchyard. The setup, procedure, vehicle consists, and instrumentation used in the tests are described.

It must be emphasized that water was used as the commodity, so the total weight on rail was only 180,000 lb. instead of the normal 263,000 lb. This resulted in lower impact forces than would be expected. In Multi Tank Car Impact Tests and Analysis – Report 3: ADAMS Model Simulations of Tank Car Impact (TDC report TP 13359E), the model was validated using data from the tests described in this report and impact data was generated for simulated tank cars weighing 263,000 lb. These higher level impact results will be used by Transport Canada to define allowable impact speeds for tank cars in switchyards.

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16. Résumé

Ce rapport présente les résultats d'une série d'essais aux chocs de wagons-citernes. Ces essais ont eu lieu aux installations du Centre de technologie des transports de surface du Conseil national de recherches du Canada. Huit wagons-citernes à longrine centrale courte ont alors été utilisés. Les «rames-béliers» étaient constituées d'au plus trois wagons, et les «rames-enclumes», d'au plus cinq wagons. Quinze essais ont été réalisés pour reproduire la plupart des situations d'impact susceptibles de survenir dans une gare de triage ferroviaire. Le banc d'essai, le protocole, les configurations mises en oeuvre et l'instrumentation utilisée sont décrits dans ce rapport.

Il convient de noter que les wagons-citernes ont été remplis d'eau et avaient donc une masse brute de 180 000 lb, ce qui est en deçà de leur masse normale en charge de 263 000 lb. Cette particularité explique les forces d'impact moins grandes que prévues. Le modèle présenté dans le rapport TP 13359E du CDT, intitulé Multi Tank Car Impact Tests and Analysis – Report 3: ADAMS Model Simulations of Tank Car Impact, avait été validé à partir des résultats des essais décrits dans le présent rapport et avait servi à générer des données d'impact concernant des wagons-citernes dont la masse brute atteignait, dans la simulation, 263 000 lb. Transports Canada utilisera ces données pour établir les vitesses d'accostage admissibles dans les gares de triage pour ce qui concerne les wagons-citernes.

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EXECUTIVE SUMMARY

This project was initiated in response to a request from Transport Canada to develop a basis for regulations with respect to the structural integrity of railway tank cars, to refine allowable impact speeds for rail cars in switchyards, and to produce guidelines for inspection criteria. It was a continuous study from the static and dynamic test (1) conducted in 1995, to the development of the ADAMS impact model (2) in 1996. The ADAMS model revealed phenomena that could affect existing Transport Canada regulations. The validation of the model was only based on the data obtained from single car impact tests. The multi-car impact tests were required to further validate the model and to provide a base for the improvement of the regulations. The results of this work may also be applied by tank car manufacturing companies to improve product designs.

The project consisted of three parts: yard impact testing, fluid impact model, and ADAMS model. This report describes the yard testing. The fluid impact model (report not published) and ADAMS model are reported separately.

The yard impact testing was conducted at the impact test facility of the Centre for Surface Transportation Technology (CSTT), National Research Council Canada. Eight stub sill tank cars were used in the tests; the maximum number of hammer tank cars was three and the maximum number of anvil tank cars was four. Water was used as the tank car commodity. A concrete-filled tank car available at the CSTT was added to the end of the anvil cars so that the actual maximum number of anvil cars was five. Fifteen different cases were tested to cover most of the situations that would occur in the practical operations of a railway switchyard. The setup, procedure, vehicle consists, and instrumentation used in the tests are described. The effects of various factors on the impact forces, as determined by analysis of the test data, are discussed.

The test results show the following characteristics:

- The maximum impact force at the striking ends generally increases with the impact speed exponentially. Controlling the impact speed is the most effective way of limiting the impact force and protecting the tank car structure from damage.

- The maximum impact force from a single hammer car or a single anvil car is lower than that from a multi-car impact at a given speed. However, the maximum impact force increases only marginally when the number of hammer cars or anvil cars increases from two to three. Based on this, it is predicted that the maximum impact force measured using the three cars should not be significantly different from that using more than three cars. This means the impact force obtained from the tests should be representative of a general multi-car impact in a railway switchyard.

- At the same impact speed, empty cars always generate a lower impact force than loaded cars.

- The maximum impact force generally occurs at the striking coupler. Even when the first hammer car or the first anvil car is empty, the impact forces on the couplers next to the striking coupler are generally lower than those at the striking coupler. This phenomenon needs further investigation during the model simulation.

- The impact forces generated on the hammer cars would not differ from those on the anvil cars if their conditions were the same.

- The longitudinal accelerations on the tank car generally increase with the impact speed. However, the data are usually very scattered and may not give an accurate indication of the impact force acting on the car. In other words, it is not as reliable as the impact force measured from the instrumented couplers.

Most of the characteristics described above are basically consistent with the predictions of the ADAMS model (2) developed in the previous study. The few differences between the predictions and the test data are discussed in the ADAMS model report (3).

It should be emphasized that water was used as the commodity and the total weight on rail was less than normal weight on rail when sulphuric acid is in the tank. Because of this, the impact forces reported are less than would be expected if tanks were loaded to the normal 263,000 lb. The ADAMS model was used to predict the impact forces produced, for the various cases, when the loaded tank car weight is 263,000 lb. and these results are reported in the ADAMs model report (3).

References

1. Militaru, D., *Tank Car Stub Sill Analysis*, Centre for Surface Transportation Technology, National Research Council Canada, Technical Report No. CSTT-RYV-CAT-026, May 1996.
2. Dong, R. and Militaru, D., *Dynamic Structural Characterization of Stub Sill Tank Cars Utilizing ADAMS and ANSYS Simulation Models*, Centre for Surface Transportation Technology, National Research Council Canada, Technical Report No. CSTT-RYV-TR-010, March 1997.
3. Xu, J. Z. and Dong, R., *Multi Tank Car Impact Tests and Analysis – Report 3: ADAMS Model Simulations of Tank Car Impact*, TP 13359E, Centre for Surface Transportation Technology, National Research Council Canada, published by Transportation Development Centre, October 1998.

SOMMAIRE

Cette étude faisait suite au projet de Transports Canada d'élaborer les bases d'une réglementation concernant l'intégrité structurale des wagons-citernes, de modifier, au besoin, les vitesses d'accostage admissibles dans les gares de triage, et de mettre au point des lignes directrices sur les critères d'inspection des wagons-citernes. Elle s'inscrivait dans le prolongement d'essais statiques et dynamiques (1) menés en 1995 et a débouché sur la mise au point du modèle ADAMS (2), en 1996. Ce modèle a mis au jour des phénomènes qui pourraient avoir des incidences sur la réglementation actuelle de Transports Canada. Le modèle n'avait été validé que pour des essais aux chocs de wagons-citernes uniques. D'autres essais mettant en jeu des ensembles de wagons s'imposaient donc pour valider de façon plus complète le modèle et fournir une assise solide à la nouvelle réglementation projetée. Les résultats des présents travaux peuvent également servir aux constructeurs de wagons-citernes désireux de perfectionner leurs produits.

L'étude se composait de trois volets : essais aux chocs en gare de triage, modélisation des effets hydrodynamiques du chargement des wagons-citernes et modélisation ADAMS. Le présent rapport est consacré aux essais en gare de triage. La modélisation hydrodynamique et la modélisation ADAMS ont fait l'objet de rapports séparés (le premier n'a pas été publié).

Les essais en gare de triage ont eu lieu aux installations du Centre de technologie des transports de surface du Conseil national de recherches du Canada. Huit wagons-citernes à longrine centrale courte ont alors été utilisés. Les «rames-béliers» étaient constituées d'au plus trois wagons, et les «rames-enclumes», d'au plus quatre wagons, plus un wagon-citerne rempli de béton qui se trouvait sur les lieux et qui a permis de porter à cinq le nombre maximal de wagons-enclumes. Les wagons-citernes étaient remplis d'eau. Quinze essais ont été réalisés pour reproduire la plupart des situations d'impact susceptibles de survenir dans une gare de triage ferroviaire. Le banc d'essai, le protocole, les configurations et l'instrumentation utilisés sont décrits dans ce rapport qui présente aussi les effets de différents facteurs sur les forces d'impact, tels qu'ils se dégagent de l'analyse des résultats d'essais.

Les résultats des essais ont permis de conclure ce qui suit :

- La force d'impact maximale augmente exponentiellement selon la vitesse d'impact. La limitation de la vitesse d'accostage est le plus sûr moyen de limiter la force de l'impact et de protéger le wagon-citerne contre tout dommage structural.

- La force d'impact maximale engendrée par un seul wagon-bélier ou wagon-enclume est inférieure à celle associée, à une vitesse donnée, à la collision de rames formées de plusieurs wagons. Toutefois, l'augmentation de la force

d'impact maximale demeure faible lorsque le nombre des wagons (béliers ou enclumes) passe de deux à trois. Cette constatation mène à prédire que la force d'impact maximale engendrée par trois wagons ne devrait pas être sensiblement différente de la force générée par plus de trois wagons. En d'autres termes, la force d'impact mesurée aux essais devrait être représentative des forces associées à une collision de wagons multiples dans une gare de triage.

- À vitesse d'impact égale, des wagons vides génèrent toujours une force d'impact plus faible que les wagons chargés.

- La force d'impact maximale se produit généralement à l'attelage du premier wagon de la rame-bélier (attelage de choc). Même lorsque ce wagon, ou le premier wagon-enclume, est vide, les forces d'impact sur les autres attelages des rames impliquées sont généralement plus faibles qu'à l'attelage de choc. Ce phénomène doit être étudié plus avant par modélisation.

- Les forces d'impact exercées sur les wagons-béliers ne seraient pas différentes de celles encaissées par les wagons-enclumes si les conditions étaient les mêmes.

- Les accélérations longitudinales du wagon-citerne augmentent généralement avec la vitesse d'impact. Les valeurs sont toutefois très variables et peuvent ne pas donner une idée précise de la force d'impact agissant sur le wagon. En d'autres termes, ce paramètre n'est pas aussi fiable que les forces d'impact mesurées sur attelages instrumentés.

La plupart des constatations ci-dessus concordent essentiellement avec les prévisions du modèle ADAMS (2) mis au point à une étape antérieure du projet. Les rares différences entre ces prévisions et les résultats des essais sont abordées dans le rapport consacré au modèle ADAMS (3).

Il convient de noter que les wagons-citernes ont été remplis d'eau et avaient donc une masse brute inférieure à celle de wagons-citernes remplis d'acide sulfurique. Cette particularité explique les forces d'impact moins grandes que prévues pour des wagons-citernes dont la masse s'élève normalement à 263 000 lb. Le modèle ADAMS a été utilisé pour prévoir les forces d'impact associées, sous différents scénarios d'impact, à un wagon-citerne chargé dont la masse brute atteint 263 000 lb, résultats présentés dans le rapport consacré au modèle ADAMS (3).

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1. Militaru, D., *Tank Car Stub Sill Analysis,* Centre de Technologie des transports de surface, Conseil national de recherches du Canada, Rapport technique N°. CSTT-RYV-CAT-026, Mai 1996.
2. Dong, R. and Militaru, D., *Dynamic Structural Characterization of Stub Sill Tank Cars Utilizing ADAMS and ANSYS Simulation Models*, Centre de Technologie des transports de surface, Conseil national de recherches du Canada, Rapport technique N°. CSTT-RYV-TR-010, Mars 1997.
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1. INTRODUCTION

Railway stub-sill type tank cars are often used to transport dangerous goods. Their damage may result in the loss of property and may have serious impacts on safety, life, and the environment. It is generally believed that high impact force in the railway switchyard is one of the major causes of crack initiation or even direct damage to the tank cars. In 1995, a series of static and dynamic tests [1] were carried out at the Centre for Surface Transportation Technology (CSTT), National Research Council Canada (NRC), as the first step in understanding the characteristics of the impact forces and stresses within stub-sill tank cars. To further investigate the behavior of the stub-sill tank cars under impact, a tank car impact model utilizing the state-of-the-art computer simulation software package, ADAMS (Automatic Dynamic Analysis of Mechanical Systems), was developed at CSTT [2]. The theoretical model was validated by the test data obtained.

In October 1997, Transport Canada contracted NRC's Centre for Surface Transportation Technology to conduct a series of dynamic impact tests using CSTT's impact facility. The objectives were to provide more tank car impact force data under various vehicle configurations and operating conditions, to develop a new fluid-flow model, and to further validate the previously developed tank car impact model. The series of dynamic impact tests were conducted between October 1997 and December 1997. The test setup, procedure, vehicle configurations, tank car characteristics, and the instrumentation are described in this report. The test data were analyzed and the effects of various factors on the impact forces were investigated.

2. TEST SETUP

2.1 Test Consists

The test consists were designed to cover most of the car configurations that would occur in practical operations in a railway switchyard. They were classified into six groups in terms of the test purposes, as shown in Figures 1 to 6. The Group 1 tests were designed to investigate the effects of the number of hammer cars on the impact force. The number of the anvil cars was fixed in this test group. Among the five anvil cars, four were water-filled tank cars (98% fill level) and the remaining one was a concrete-filled tank car in Cases 2 and 3. In case 1, all five anvil cars were water-filled tank cars (98% fill level). The Group 2 and Group 3 tests were designed to investigate the effects of the number of anvil cars on the impact force. In Group 2 tests, three water-filled tank cars were used as hammer cars, while the number of anvil cars was varied. In Group 3 tests, a single water-filled hammer car was used, with the number of anvil cars varied. In Group 4, three water-filled tank cars were used to impact five anvil cars. However the first hammer car in the test group was empty. The Group 5 test was a repeat of the Group 1 test except that all hammer cars in this group were empty. In Group 6 tests, the first anvil car was empty. This test group was

designed to check whether the highest magnitude of impact forces occurs at the striking coupler or other coupler locations.

2.2 Tank Car Characteristics

The Photographs of the hammer and anvil tank cars are shown in Photograph 7 and 8. A total of 9 tank cars were used in the tests and they are listed in the following table:

Car Number	Year Built	Capacity	Comments
Prox 13764 (NRC1)	05-67	11585Gal/52666L	Instrumented car
Prox 13013 (NRC2)	07-68	11493Gal/52248L	
Prox 14252 (NRC3)	09-73	11470Gal/52144L	
Prox 14281 (PROCOR)	05-73	11472Gal/52153L	
Prox 14277 (PROCOR)	05-73	11424Gal/51935L	
Prox 14258 (PROCOR)	11-73	11440Gal/52007L	
Prox 14264 (PROCOR)	04-73	11425Gal/52062L	
Prox 14259 (PROCOR)	11-73	11421Gal/51920L	
Prox 13274 (NRC4)			Concrete filled

One of the tank cars was filled with concrete and it was positioned at the end of the anvil car consist. Five of the tank cars were provided by PROCOR. All of the cars were previously used in service. They have approximately the same capacity. The tank car used for instrumentation is representative and its characteristics are described below:

Tank Car Classification:	111A100W
Type of Car:	Stub Sill Design with Continuous Pad
Year of Construction:	1967
Truck Type:	Conventional 3-piece truck (36"/914.4mm wheels)
Capacity:	11585 Gal Imp / 52666 Liters
LD LMT:	210100 lbs / 95300 KG
LTWT:	52900 lbs / 24000 KG
Gross Weight at Rail:	263,000 lbs / 119300 KG
Car Length over Striker Faces:	39'-9" / 12.116m
Distance between Truck's Pivots:	28'-10" / 8.788m
Coupler Type:	Type E or F Double Shelf
Tank Length:	36'-9.5" / 11.214m
Tank Diameter:	98.5" / 2.502m
Tank Shell:	0.5" / 12.7mm – A515 steel
Type of Shell:	Not Insulated
Surge Pressure Device:	65 100 psi Frangible Disc
Typical Load:	Sulfuric Acid

It should be noted that water was used as commodity and the total weight on rail was less than normal weight on rail when sulphuric acid was in the tank. Because of this, the impact forces reported in this report are less than what would be expected if tanks were loaded to the normal 263,000 pounds. The ADAMS model will be used to predict the impact forces produced, for the various cases, when the loaded tank car weight is 263,000 lbs. These results will be reported in the report on the ADAMS model.

2.3 Instrumentation

The instrumentation used during the tests was designed to measure and record various aspects of the tank cars' responses during a variety of impacts with different impact speeds. The instrumentation used for the impact tests is identified in Table 1.

Table 1. Instrumentation for impact tests

Items Measured	Transducer/Equipment
Impact force	Dynamometer coupler
Impact speed	Speed transducer or laser speed device
Longitudinal acceleration of the instrumented car	Accelerometer
Pressure inside the tank of the instrumented car	Pressure transducer
Longitudinal displacement at the striking coupler	Displacement transducer
Vertical displacement at the striking coupler	Displacement transducer
Vertical displacement of car body at left side of front axle	Displacement transducer
Vertical displacement of car body at left side of rear axle	Displacement transducer
Vertical displacement of car body at right side of front axle	Displacement transducer
Vertical displacement of car body at right side of rear axle	Displacement transducer

Three dynamometer couplers, strain gauged and calibrated by NRC personnel, were installed in the first anvil car and in another tank car, which was used as either a hammer car or an anvil car in terms of the test consists. The locations of the couplers for each test configuration were shown in Figures 1-6.

The speed of the test car was measured by two different devices, a Patriot model PV-2000B position/velocity transducer and a laser sensor, model WL12L, manufactured by SICK Optic-Electronic, Inc. The velocity transducer (Photograph 1) consists of a precision DC generator physically coupled to a constant diameter take-up drum and return spring. The take-up drum was wound with a fine steel wire, extending to the test car. As the hammer car rolled down the impact hill, the take-up drum rotated, and an output voltage signal directly proportional to the velocity of the car was produced by the generator. The laser speed device (Photograph 2) was mounted on a tripod and positioned beside the impact track near the impact location. As the test car moved past the speed device, the laser detected the presence of two reflective strips mounted on the

side of the test car. The reflective strips were positioned a predetermined distance apart. As the laser detected the passage of each reflective strip it output a pulse that was recorded by the data acquisition system. The data acquisition system calculated the time interval between the two pulses. The velocity of the test car was calculated by dividing the known distance between the two reflective strips by the recorded time interval.

Three accelerometers (Photograph 3) were mounted on the first anvil car (instrumented car) to provide the longitudinal acceleration data during the impact. Five pressure transducers (Photograph 4) were installed at different locations of the tank to measure the pressure variations during the impact. The locations of these transducers are illustrated in Figure 7. In addition, several displacement transducers were installed to measure the longitudinal and vertical displacement of the chosen coupler and the lift of the car (Photograph 5 and 6). Their locations are also shown in Figure 7.

The data acquisition system used in the tests comprises an Analog Devices 2B31L instrumentation amplifier and signal condition cards, a Burr-Brown PCI-20000 data acquisition system, and a PC 486 computer system. The analog signals yielded by the sensors were filtered using a 60 dB per decade low pass filter (3 dB down point, at 600 Hz). The channel layout of the impact tests is listed in Table 2.

Table 2. Channel layout for the impact tests

Channel	Channel name	Channel description
1	CPLR6A	Coupler force
2	CPLR6B	Coupler force
3	SPEED2	Impact speed
9	CPLR1A	Coupler force
10	CPLR1B	Coupler force
17	ACC1	Acceleration #1
18	ACC2	Acceleration #2
19	P1	Pressure #1
20	P2	Pressure #2
21	P3	Pressure #3
22	P4	Pressure #4
23	P5	Pressure #5
24	D1	Longitudinal displacement of coupler
25	D2	Vertical displacement of coupler
26	D3	Vertical displacement of car body at left side of front axle
27	D4	Vertical displacement of car body at left side of rear axle
28	D5	Vertical displacement of car body at right side of front axle
29	D6	Vertical displacement of car body at right side of rear axle
30	CPLR5A	Coupler force
31	CPLR5B	Coupler force
32	ACC3	Acceleration #3

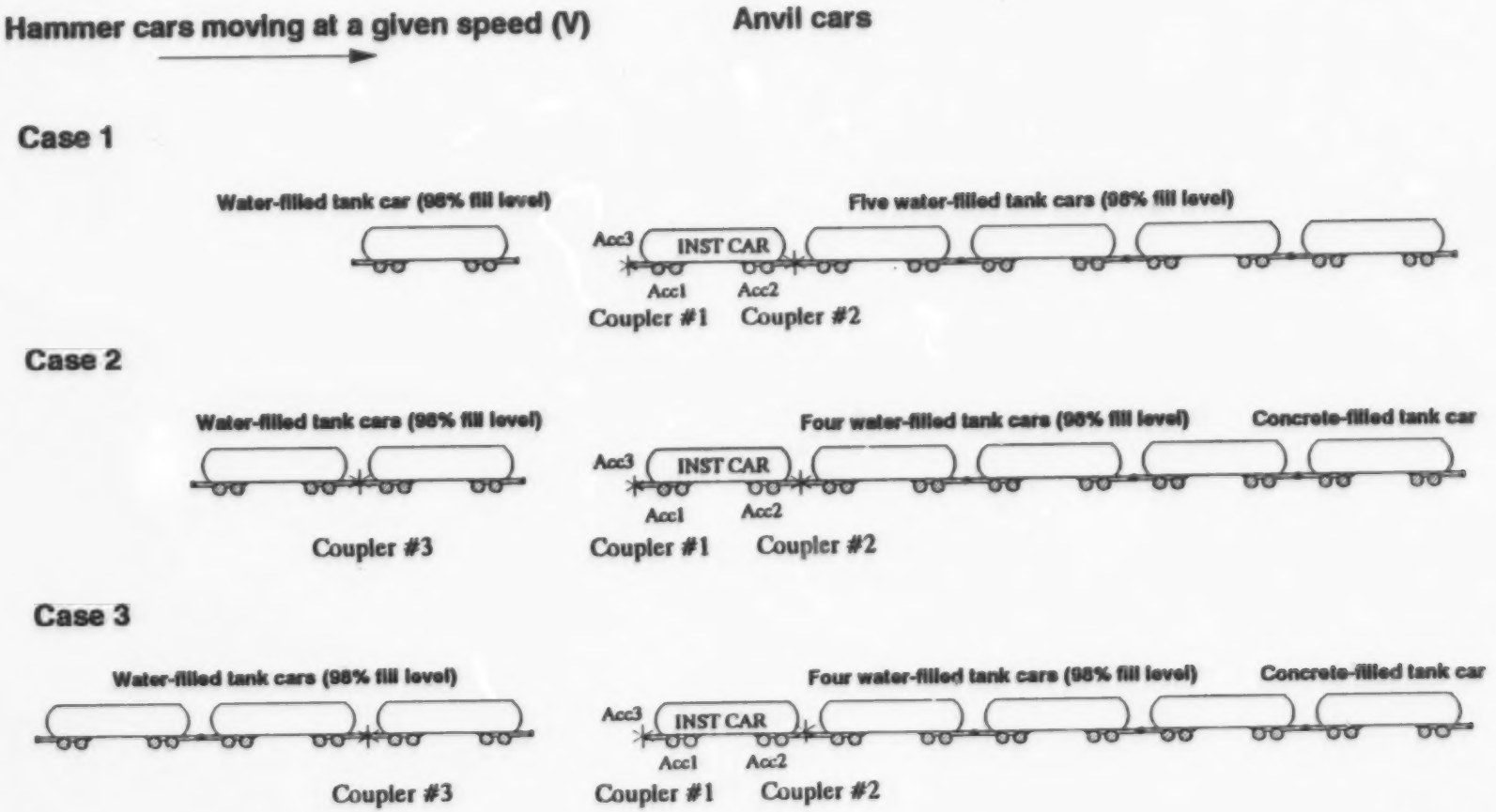


Figure 1. Tank car configurations in Group 1 Tests

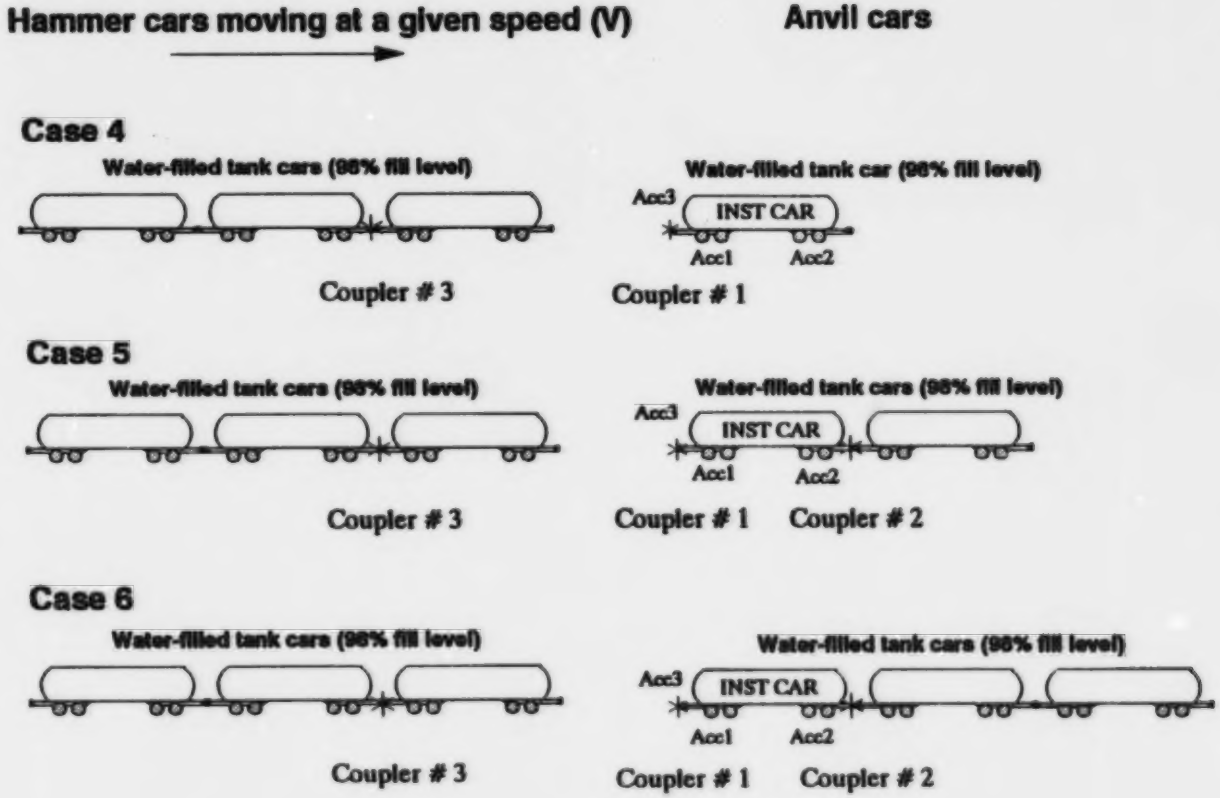


Figure 2. Tank car configurations in Group 2 Tests

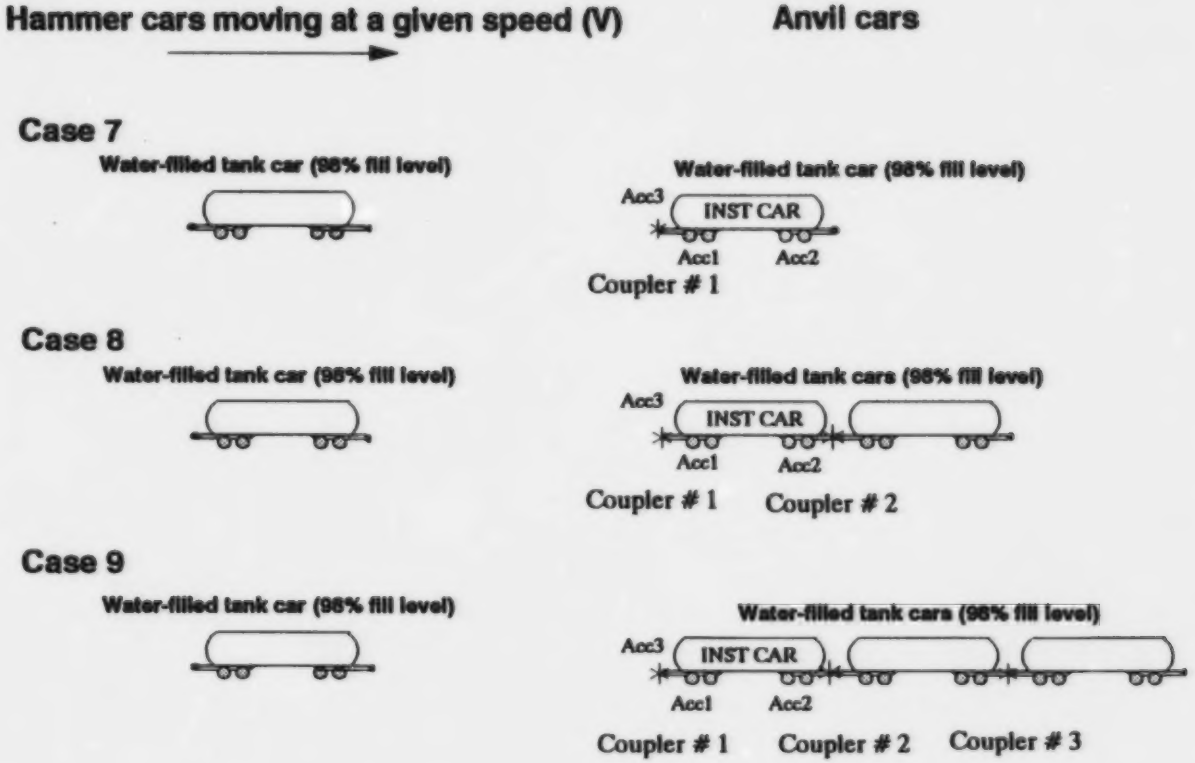


Figure 3. Tank car configurations in Group 3 Tests

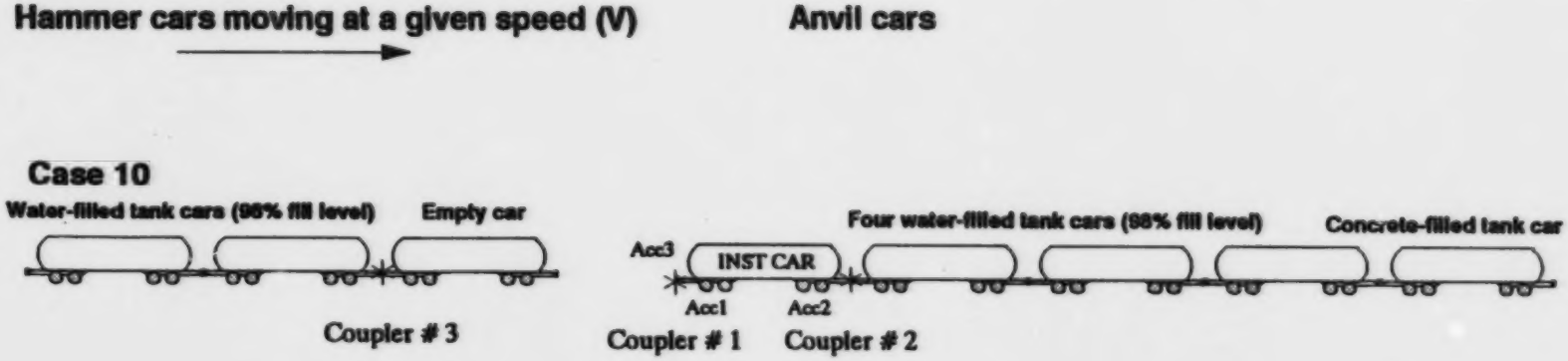


Figure 4. Tank car configurations in Group 4 Tests

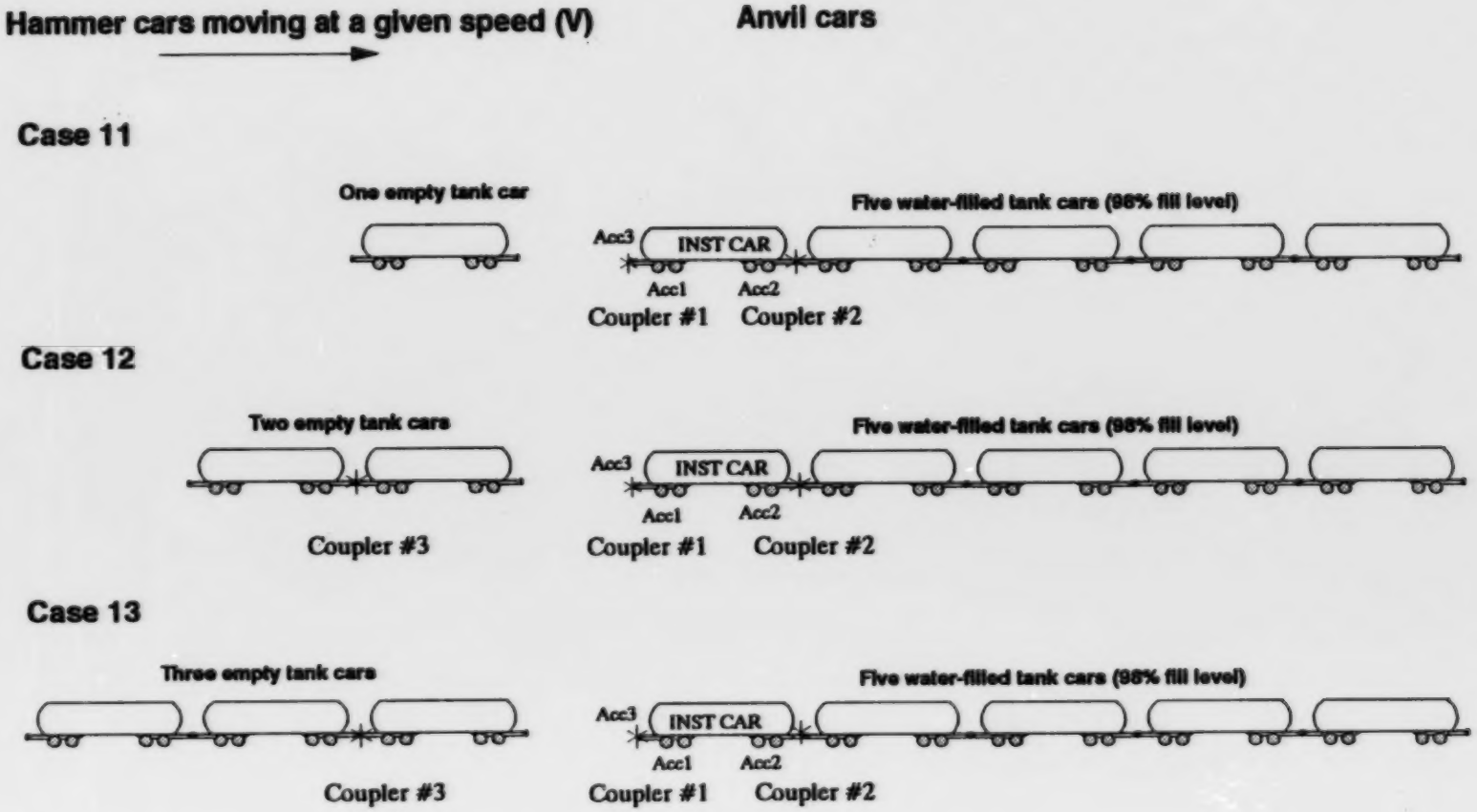


Figure 5. Tank car configurations in Group 5 Tests

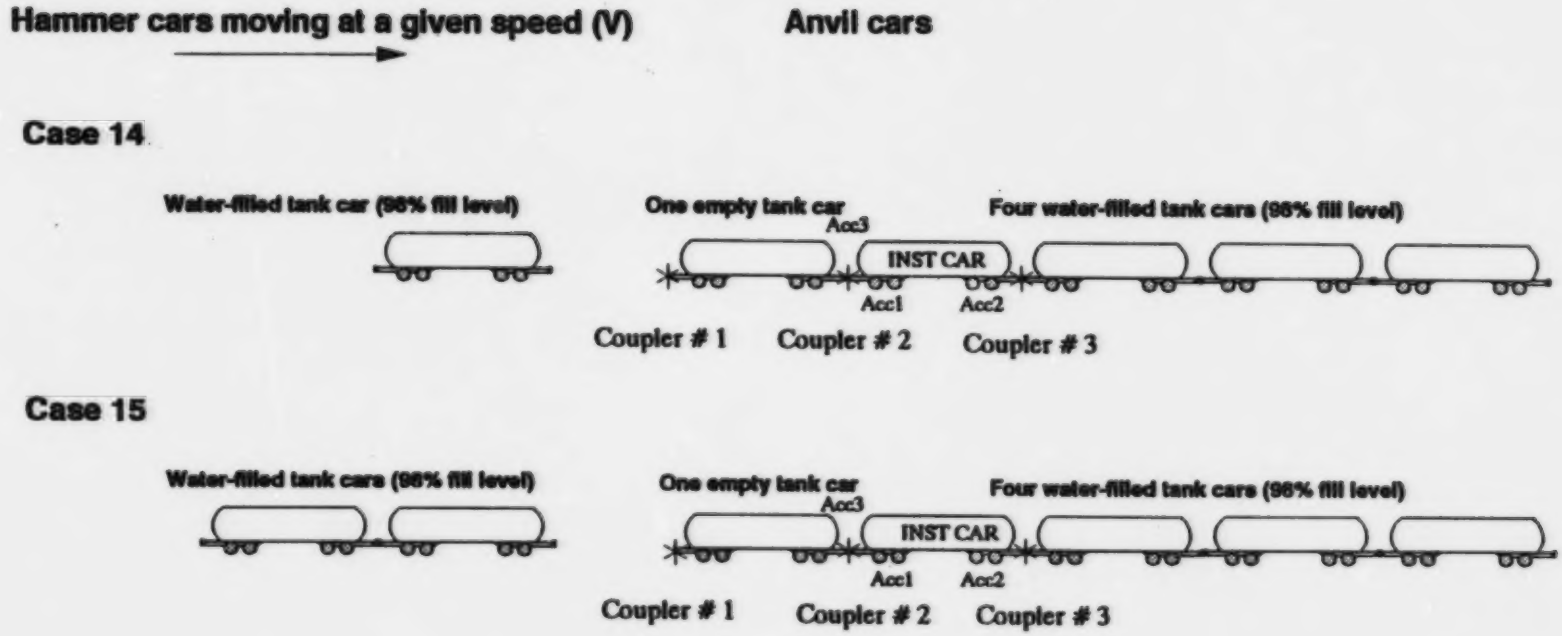
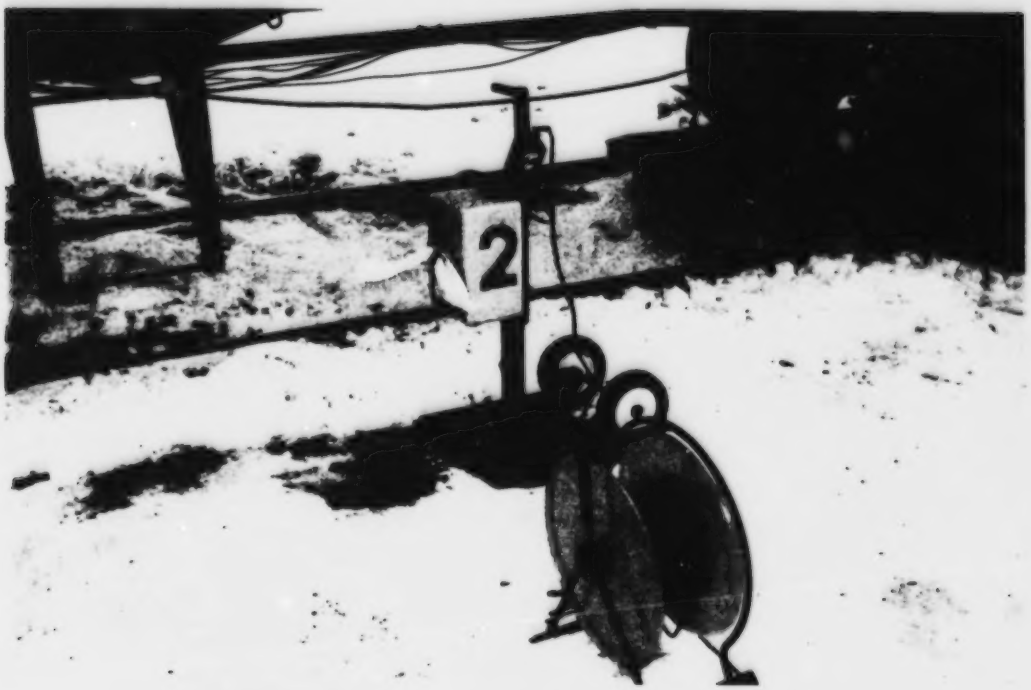
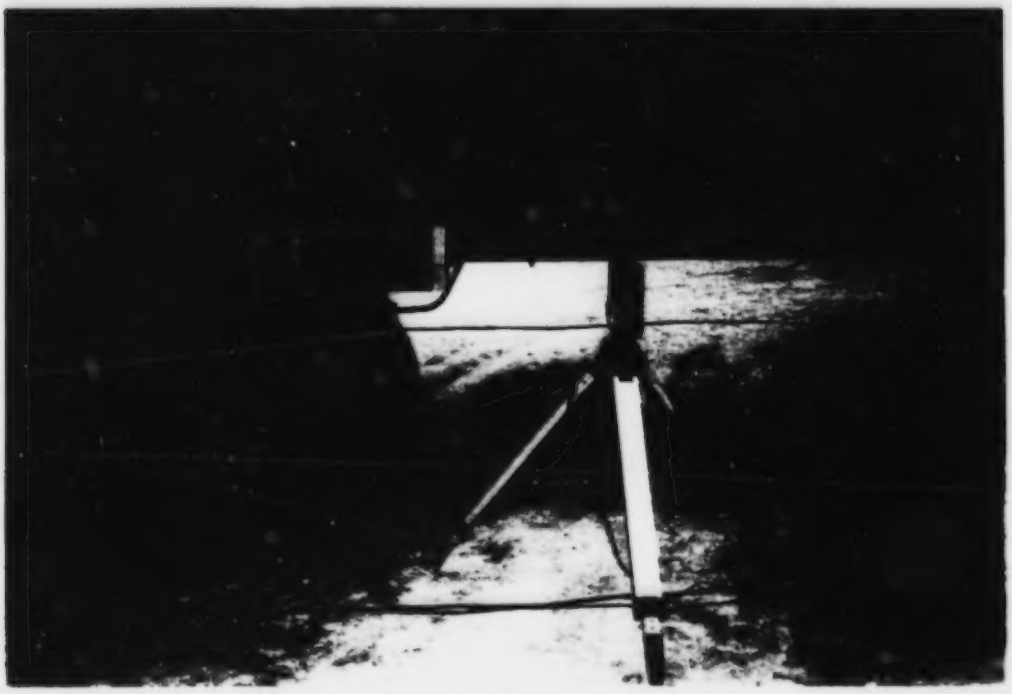


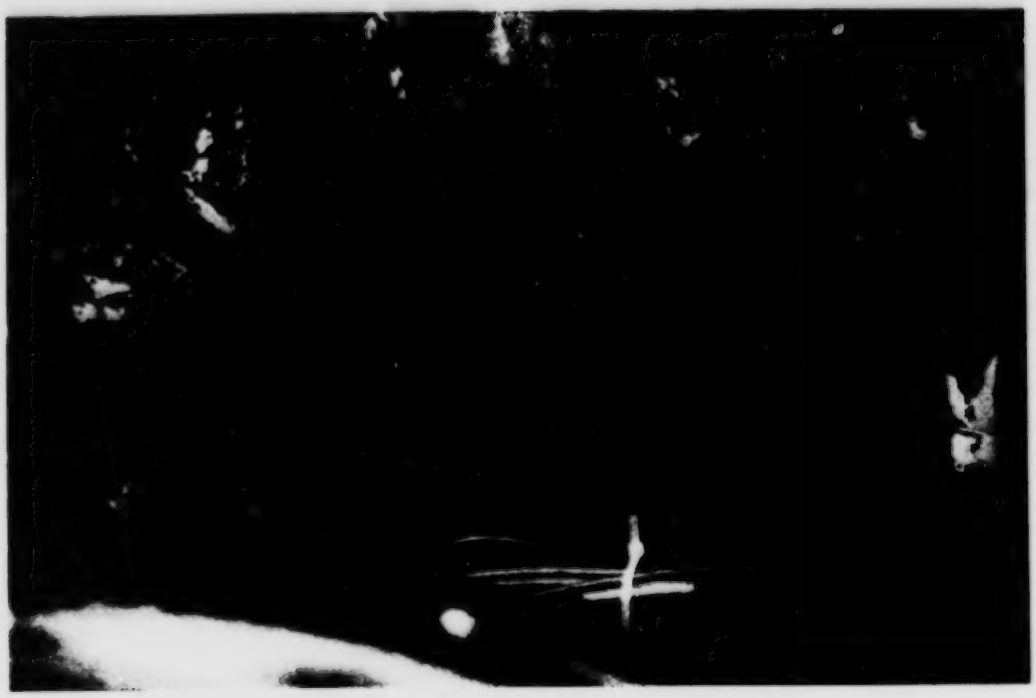
Figure 6. Tank car configurations in Group 6 Tests



Photograph 1: The velocity transducer apparatus

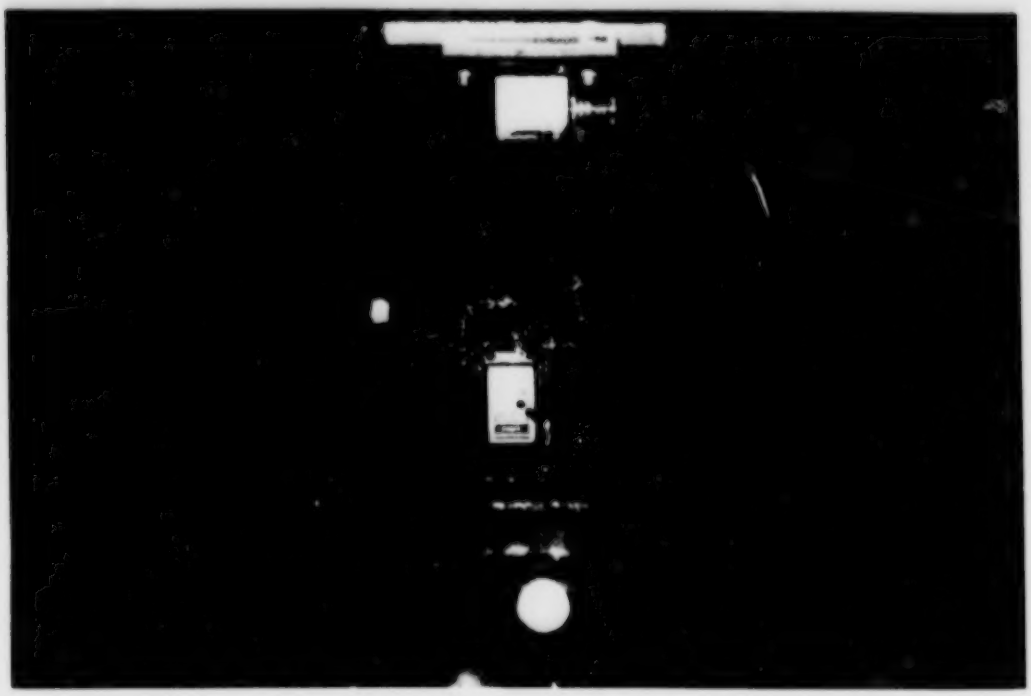


Photograph 2: Laser sensor for speed measurement

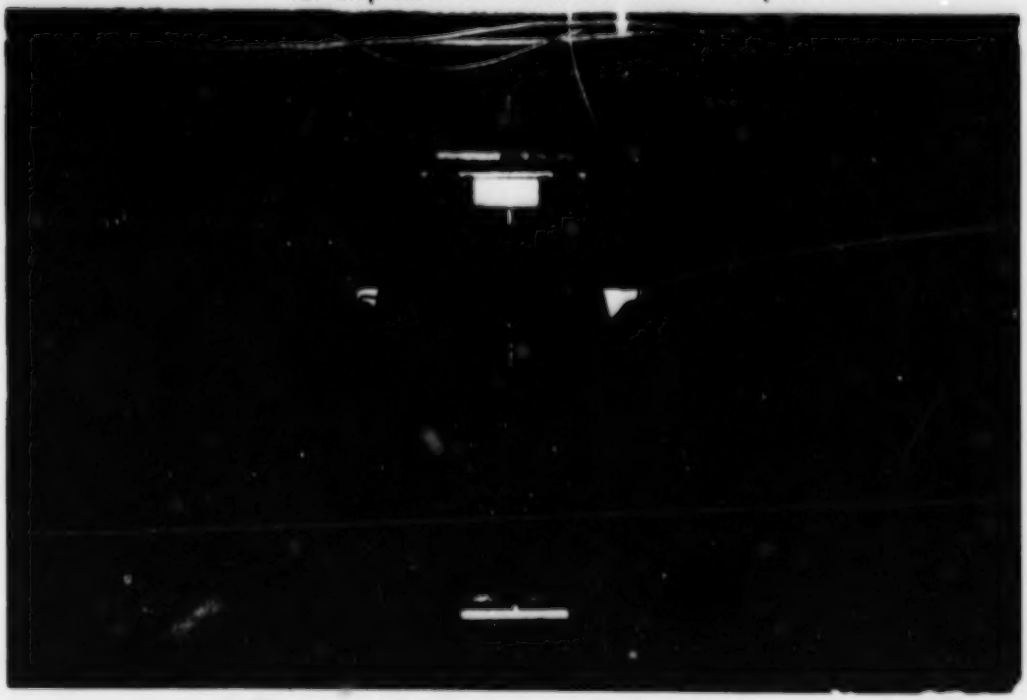


Photograph 3: Accelerometer

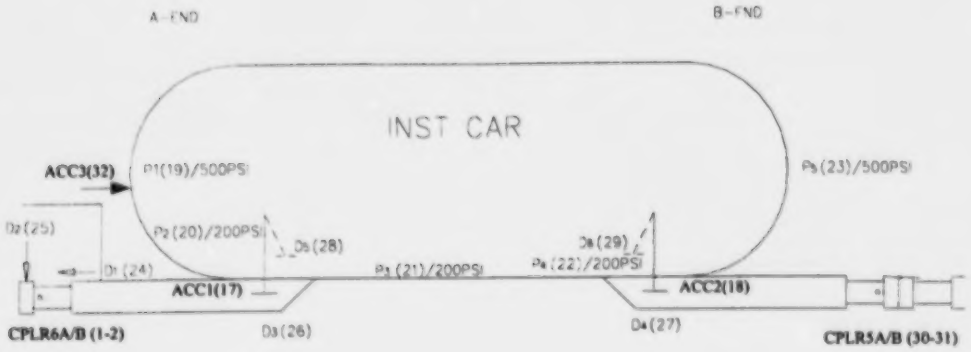
Photograph 4: Pressure transducer



Photograph 5: Longitudinal and vertical displacement transducers for displacement measurement at coupler #1



Photograph 6: Vertical displacement transducer for measuring car lift



Note: The number in the bracket is the channel no. of the data acquisition system as in Table 2.

CPLR6A(1): Coupler force	CPLR6B(2): Coupler force	SPEED2(3): Impact speed
CPLR1A(9): Coupler force	ACC1(17): Acceleration #1	ACC3(32): Acceleration #3
ACC2(18): Acceleration #2	P1(19) Pressure #1	P2(20): Pressure #2
P3(21): Pressure #3	P4 22): Pressure #4	P5(23)Pressure #5
CPLR5A(30): Coupler force	CPLR5B(31): Coupler force	

D1(24): Longitudinal displacement of coupler D2(25): Vertical displacement of coupler
D3(26): Vertical displacement of car body at left side of front axle
D4(27):Vertical displacement of car body at left side of rear axle
D5(28): Vertical displacement of car body at right side of front axle
D6(29):Vertical displacement of car body at right side of rear axle
CPLR1B(10): Coupler force (Not shown on this diagram, see tank car configuration diagrams)

Figure 7. Locations of sensors on the instrumented car

3. TEST RESULTS

The impact tests of tank cars were conducted at CSTT impact facilities, shown in Photographs 7 and 8. A total of 280 tests were carried out for 15 different test cases. A list of the tests is given in Appendix 1. To get repeatable and reliable data, the impact tests were repeated five times for each speed range. The test speed range was designed such that the impact force would not exceed 1,000 klb.

3.1 Impact Forces

Impact force is an important measure used to identify impact severity, which is closely related to the impact speed. The impact forces were measured using the instrumented couplers. The time histories of the impact forces at different coupler locations were recorded by the data acquisition system. For each test case, the peak impact forces at different coupler locations were plotted versus the speed, as shown in Figures 8 to 22. The values of the peak impact forces at different locations were shown in Tables 3 to 17.

3.1.1 Effect of the number of hammer cars

To investigate the effects of the number of hammer cars on the impact force, various numbers were used in the tests, one hammer car in Case 1, two hammer cars in Case 2, and three hammer cars in Case 3. All hammer cars were 98% full. In each case, five anvil cars were used. In case 2 and case 3, four of these anvil cars were tank cars (98% filled) and one was a concrete-filled tank car. In case 1, all five anvil cars were tank cars (98% filled). As it can be seen from Figures 8 to 10, the maximum magnitude of peak impact forces occurred at the striking coupler, namely coupler #1, in all test cases. At low impact speed (less than 4 mph), the number of hammer cars had little effect on the maximum magnitude of peak impact force. When the impact speed was beyond 5 mph, the peak impact force at coupler # 1, measured in Case 1, was significantly lower than those measured in Case 2 and Case 3, as also shown in Tables 3 to 5. However for the same speed range, the peak impact forces at coupler #1, measured in Cases 2 and 3, were only marginally different. These observations suggest that:

- At low impact speed (less than 4 mph), the number of cars has little effect on the peak impact force.

- At high impact speed (larger than 5 mph), the maximum impact force with two hammer cars is higher than that with only one hammer car. However, increasing the number of the hammer cars from two to three influences the maximum impact force only marginally. Based on this finding, it can be predicted that further increasing the number of hammer cars would have little effect on the maximum impact force, but the high-level impact force could last longer as the number of hammer cars is increased.

These observations were consistent with the results obtained from the model simulation [2].

It should be emphasized that the loaded tank cars were only filled with water and as such were lighter than the design weight of 263,000 lbs. Therefore, the impact forces for the loaded tank cars were less than what would be expected if they weighed 263,000 lbs. Impact forces provided in this report for full tank cars must not be interpreted as those expected in normal service. The test results will be used to validate the ADAMS model and reference to the ADAMS report is advised for an estimation of the impact forces when the tank cars are loaded to 263,000 lbs.

3.1.2. Effect of the number of anvil cars

To investigate the effects of the number of anvil cars on the impact force, six cases in Group 2 and Group 3 were considered. In Group 2 tests, three water-filled tank cars were used as hammer cars, while in Group 3 tests, a single

water-filled tank car was used as a hammer car. The number of anvil cars used in these tests was varied from one to three cars. In Case 4 and Case 7, only one anvil car was used. In Case 5 and Case 8, two anvil cars were used. In Case 6 and Case 9, three anvil cars were used. All anvil cars and hammer cars were tank cars with 98% fill.

As it can be seen from Figures 11 to 16, the maximum magnitude of the peak impact forces occurred at the striking coupler in all test cases except Cases 8 and 9 in certain speed ranges. For Cases 8 and 9, in speed ranges between 5 to 6 mph, the maximum magnitude of peak impact force at coupler locations other than the striking coupler is slightly high than that at the striking coupler, as shown in Figures 15 and 16. In these cases, the peak impact forces were not high and they may not be of concern practically.

At low impact speed (less than 5 mph), the maximum magnitude of peak impact force increased slightly as the number of anvil cars increased. When the impact speed is beyond 6 mph, the peak impact force at coupler # 1, measured in Case 4, is relatively lower than those measured in Case 5 and Case 6, as shown in Tables 6 to 8. As the number of anvil car further increased from two to three, as from Case 5 to Case 6, the peak impact force at coupler #1 was also increased. However, the amount of increase was not as significant as from one anvil car to two anvil cars. In Cases 8 and 9, the change in the anvil cars had little effect on the impact forces.

These observations suggest that:

- One anvil car is not sufficient to represent a general impact situation.
- However, a large number of anvil cars, say more than 3, may not be required to represent a general impact situation for obtaining the maximum impact force.

Note also that the number of hammer cars and anvil cars were identical in Case 6. Hence the system configurations in this case was theoretically symmetrical. Thus the peak coupler forces at locations 2 and 3, obtained from the tests, were very close. This suggests that the impact forces on the hammer and anvil cars would be identical if their configurations were the same.

In Cases 3 and 6, the number of hammer cars was the same. The number of anvil cars in Case 3 was five but in Case 6 was three. Theoretically, the impact force from Case 3 should be higher than that from Case 6. Surprisingly, the impact force from Case 6 was significantly higher than that from Case 3 when the speed was higher than 7 mph. These tests were carried out on different date. The weather might have some effects on the tests. The results will be further examined in the report of the ADAMS model.

3.1.3 Effect of empty car as hammer car

The effect of an empty car as hammer car on the impact force was considered in Case 10, in which the first hammer car was empty, as shown in Figure 3, and in

Cases 11, 12, and 13. Comparing Case 10 (Figure 17) with Case 3 (Figure 10), one can observe that by using an empty tank car, the peak impact force at the striking coupler was reduced significantly. This suggests that the worse case should be when the tank cars involved in the impact are loaded. If the striking tank car is empty, either on hammer side or on anvil side, or on both, the impact force would be reduced. Comparing Cases 11, 12, and 13, with their similar consists of loaded hammer cars, one can conclude that when using empty hammer cars the impact speed can be increased by about 2 mph to generate the same level of peak impact forces as with 98% loaded hammer cars. Again, this may only be true if the commodity in the tank car has a density similar to water.

3.1.4 Impact forces at different locations

Cases 14 and 15 were designed to check whether the maximum magnitude of peak impact force would occur at the striking coupler or other coupler locations, especially at high-speed ranges. In both cases, the first anvil car was an empty one. As can be seen in Figures 22, the maximum magnitude of the peak impact forces occurred at the striking coupler for all tested speed ranges. In Case 14 (Figure 21), the maximum magnitude of the peak impact forces occurred at the striking coupler for the most of the tested speed ranges, except those between 4 and 5.5 mph. In Case 11, for the speed ranges between 5.5 to 6.5 mph, the maximum magnitude of peak impact force at coupler locations other than the striking coupler was also slightly higher than that at the striking coupler, as shown in Figures 18. However, for most of the cases, the maximum impact forces generally occurred on the striking couplers. This finding differs from the results obtained in previous model simulation [2], where the impact forces on the coupler next to the striking coupler were found to be at the same level or even larger than those at the striking coupler were. This finding needs further verification by the model simulation using the vehicle parameters measured in the tests.

3.2 Longitudinal Accelerations

The longitudinal accelerations provided an alternative means of measuring impact severity. In this study, the longitudinal acceleration data were processed using a filter cut-off frequency of 40 Hz. To obtain a correlation between the peak impact force and the maximum longitudinal acceleration, the peak impact force at the coupler installed at the striking end of the instrumented car was plotted against the maximum longitudinal accelerations that were measured on the stub sill near the striking end, as shown in Figures 23 to 37. As can be seen from these figures, the acceleration data are scattered. This means that it may not be reliable to use the acceleration data obtained in the time domain to predict the impact response of tank cars. Reference [3] suggests a systematic frequency domain method to process the acceleration data, such that a more reliable acceleration representation of the impact could be obtained.

Photograph 7: Hammer cars positioned for impact tests

Photograph 8: Anvil cars positioned for impact tests

Case 1

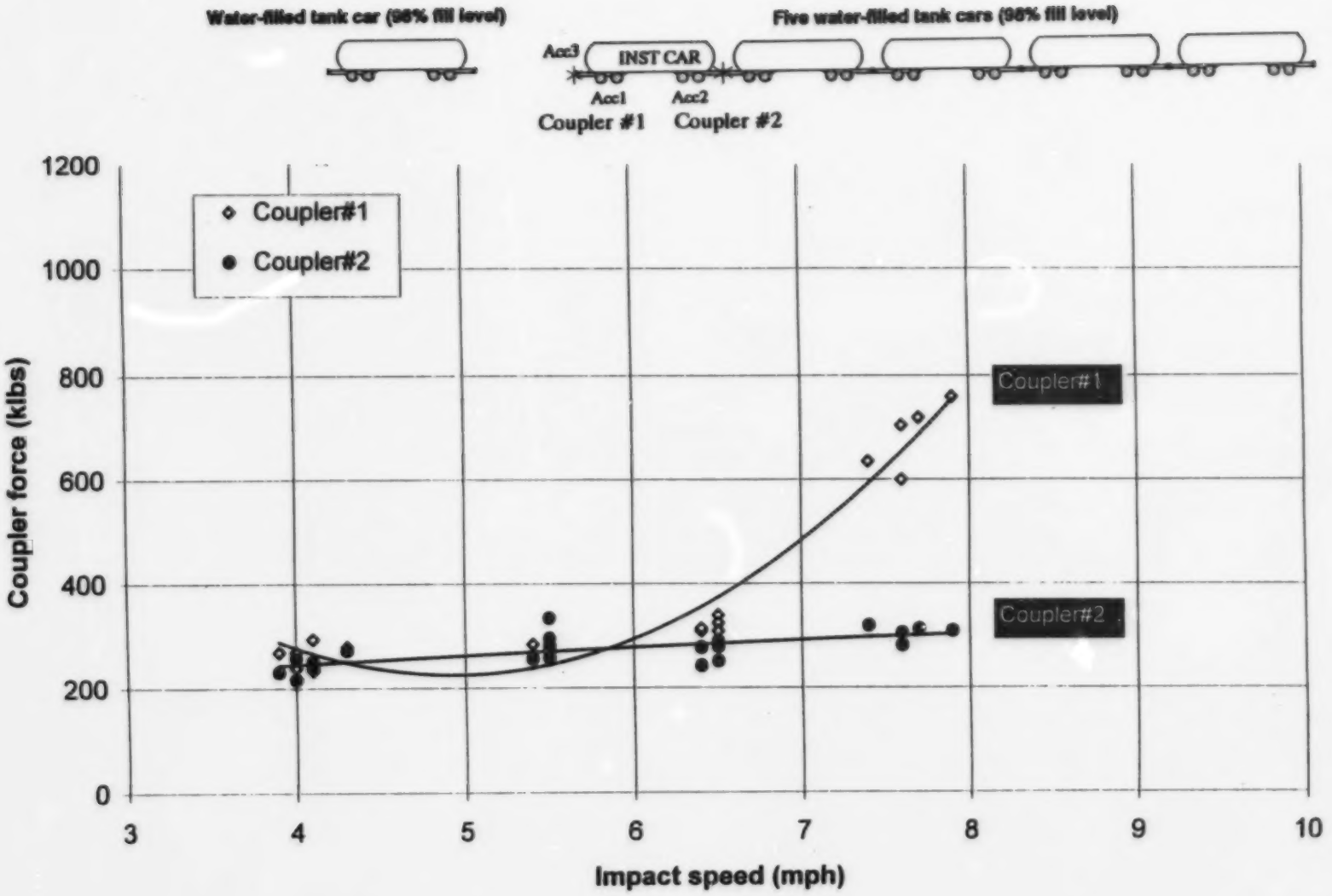


Figure 8. Maximum impact forces at different couplers versus speed for case #1

Table 3: Measured coupler forces and accelerations at different speeds for case #1

Case #1	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	Maximum Coupler Forces #2 (Klbs)	Maximum Accelerations Acc1 (g)	Maximum Accelerations Acc2 (g)	Maximum Accelerations Acc3 (g)
One loaded tank car hits five loaded anvil cars.	4.0	98%	240	217	1.9	11.6	7.8
	4.1	98%	295	252	2.9	15.6	5.9
	4.0	98%	270	258	3.3	15.7	9.3
	3.9	98%	270	232	6.8	18.6	5.1
	4.3	98%	280	274	1.9	18.9	9.9
	4.1	98%	235	240	3.6	14.8	7.4
	5.4	98%	285	257	4.0	20.2	6.0
	5.5	98%	280	296	1.8	17.8	13.9
	5.5	98%	295	273	5.4	22.7	7.9
	5.5	98%	285	335	7.4	27.7	12.1
	5.5	98%	270	259	3.2	19.3	10.5
	6.5	98%	340	290	3.0	21.4	11.1
	6.4	98%	310	278	5.0	25.0	11.4
	6.4	98%	315	243	7.1	22.6	11.5
	6.5	98%	325	280	8.0	23.3	12.5
	6.5	98%	310	252	5.8	26.5	13.1
	7.4	98%	635	320	6.3	19.4	14.7
	7.6	98%	600	306	7.2	25.6	11.8
	7.6	98%	705	282	3.3	20.9	10.8
	7.7	98%	720	314	3.7	24.9	11.8
	7.9	98%	760	310	3.2	27.5	15.7

Case 2

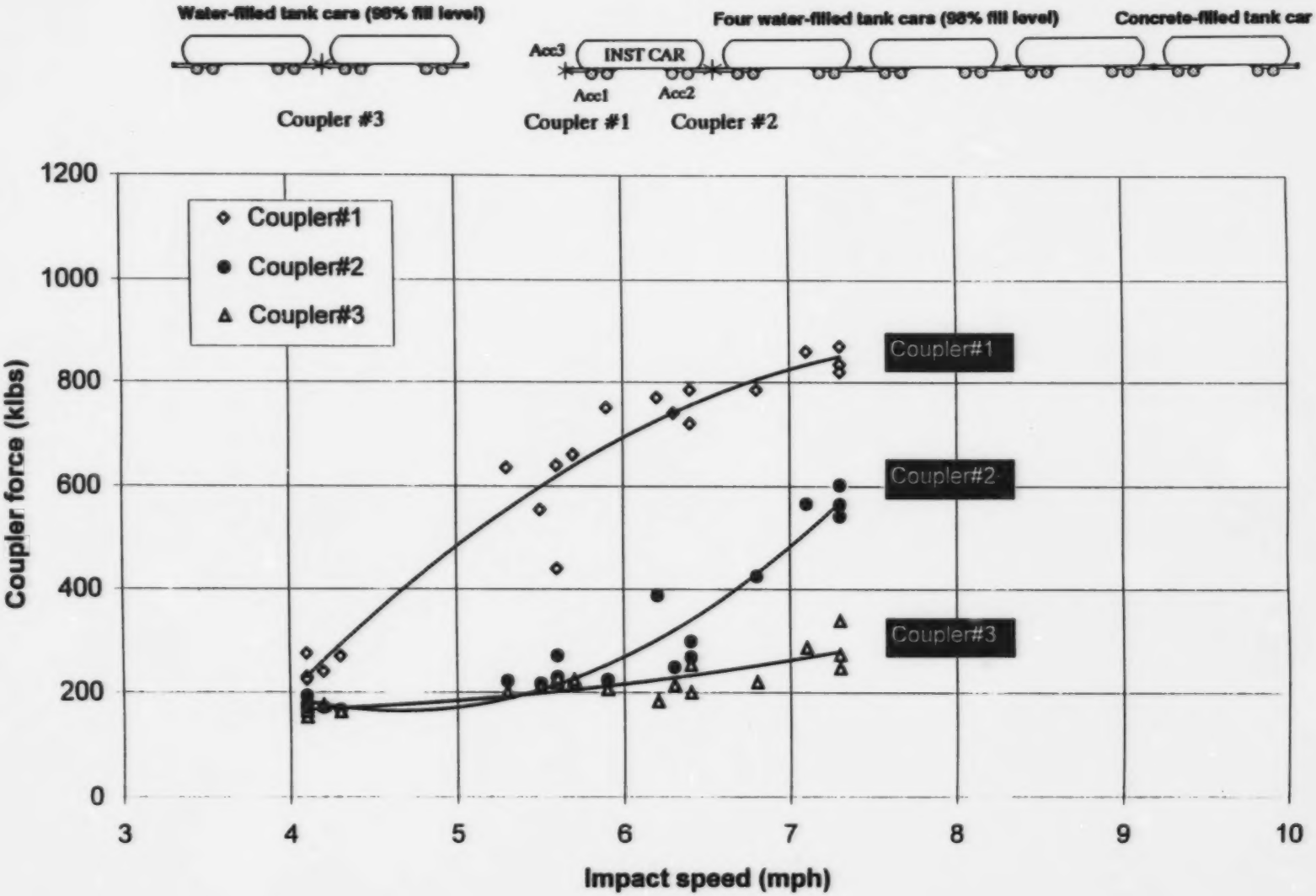


Figure 9. Maximum impact forces at different couplers versus speed for case #2

Table 4: Measured coupler forces and accelerations at different speeds for case #2

Case #2	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	#2 (Klbs)	#3 (Klbs)	Maximum Accelerations Acc1 (g)	Acc2 (g)
Two loaded tank cars hit five loaded anvil cars.	4.1	98%	230	168	153	N/A	9.2
	4.3	98%	270	167	163	N/A	6.2
	4.1	98%	275	193	164	N/A	4.7
	4.1	98%	225	176	172	N/A	6.6
	4.2	98%	240	171	175	N/A	5.9
	5.3	98%	635	222	200	N/A	23.4
	5.7	98%	660	213	224	N/A	19.7
	5.6	98%	640	271	219	N/A	23.9
	5.5	98%	555	217	211	N/A	22.7
	5.6	98%	440	230	227	N/A	23.7
	5.9	98%	750	224	206	N/A	24.9
	6.3	98%	740	249	214	N/A	24.9
	6.2	98%	770	388	183	N/A	22.2
	6.4	98%	785	268	200	N/A	24.8
	6.4	98%	720	299	253	N/A	26.2
	6.8	98%	785	425	220	15.5	21.2
	7.1	98%	860	566	287	16.6	23.0
	7.3	98%	835	602	247	14.2	23.2
	7.3	98%	820	565	273	15.7	25.2
	7.3	98%	870	542	339	18.0	26.3

Case 3

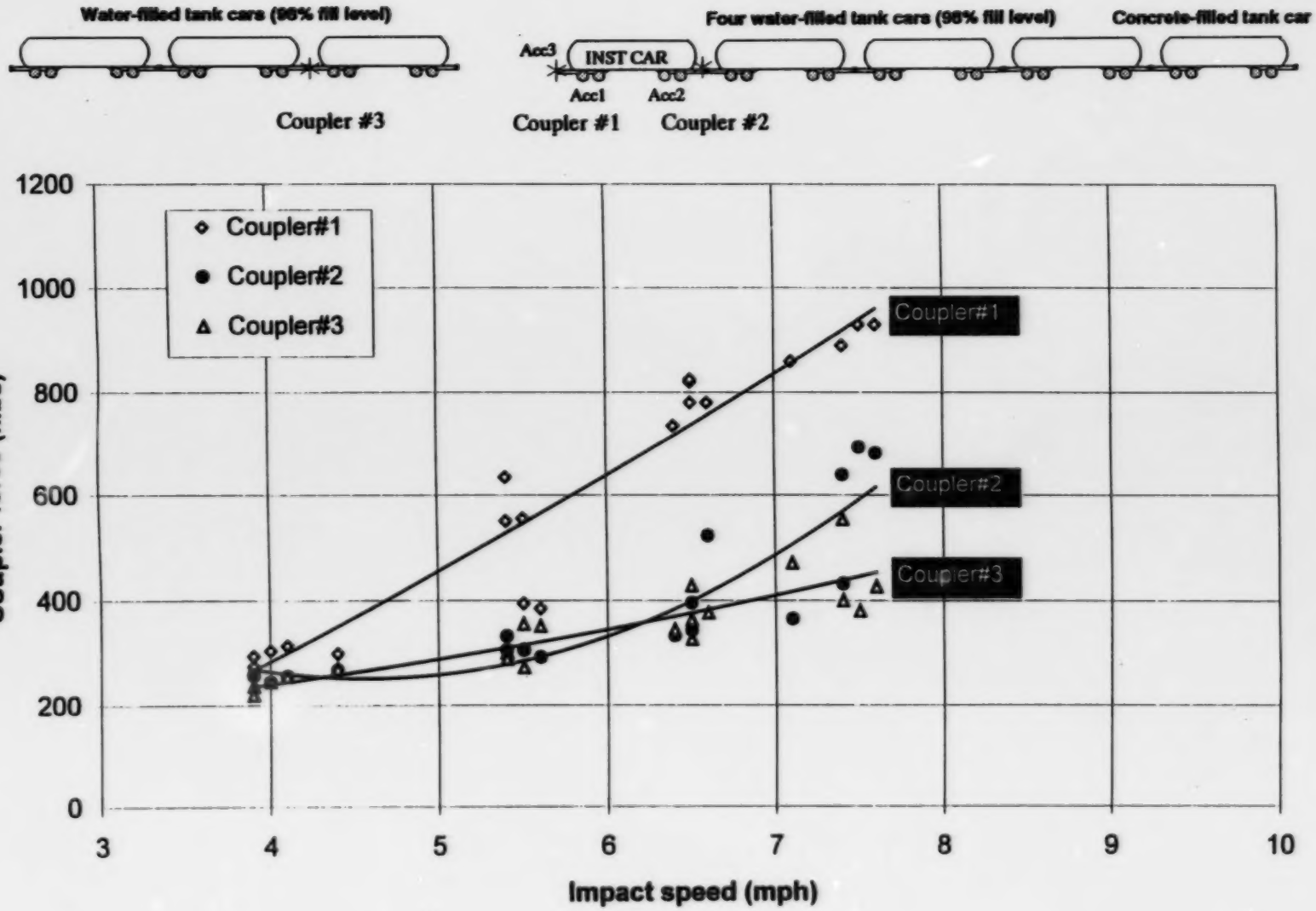


Figure 10. Maximum impact forces at different couplers versus speed for case #3

Table 5: Measured Coupler forces and accelerations at different speeds for case #3

Case #3	Impact Speed	Fill Level of Loaded Car	Maximum Coupler Forces			Maximum Accelerations		
			#1	#2	#3	Acc1	Acc2	Acc3
	(mph)		(Klbs)	(Klbs)	(Klbs)	(g)	(g)	(g)
Three loaded tank cars hit five loaded anvil cars.	3.9	98%	295	260	237	3.8	15.9	4.6
	4.4	98%	300	268	271	5.3	15.1	5.2
	4.1	98%	315	257	256	4.8	11.1	8.5
	3.9	98%	275	258	220	10.0	9.1	7.1
	4	98%	305	246	246	7.7	13.1	4.8
	5.4	98%	635	306	301	10.0	13.30	9.6
	5.5	98%	555	306	273	10.5	21.0	9.2
	5.6	98%	385	293	352	4.5	19.1	9.3
	5.4	98%	550	333	289	10.2	14.0	8.8
	5.5	98%	395	308	356	8.4	22.4	11.3
	6.5	98%	820	345	428	18.3	29.5	15.1
	6.5	98%	780	396	327	14.9	21.9	14.0
	6.6	98%	780	522	377	10.7	23.1	13.8
	6.5	98%	825	344	364	13.1	21.5	13.9
	6.4	98%	735	334	345	15.1	19.8	13.9
	7.1	98%	860	366	470	9.6	23.0	11.7
	7.4	98%	890	432	553	11.8	23.1	16.9
	7.4	98%	890	640	400	18.5	24.1	14.6
	7.6	98%	930	682	426	18.9	29.5	14.7
	7.5	98%	930	694	381	21.3	25.9	10.6

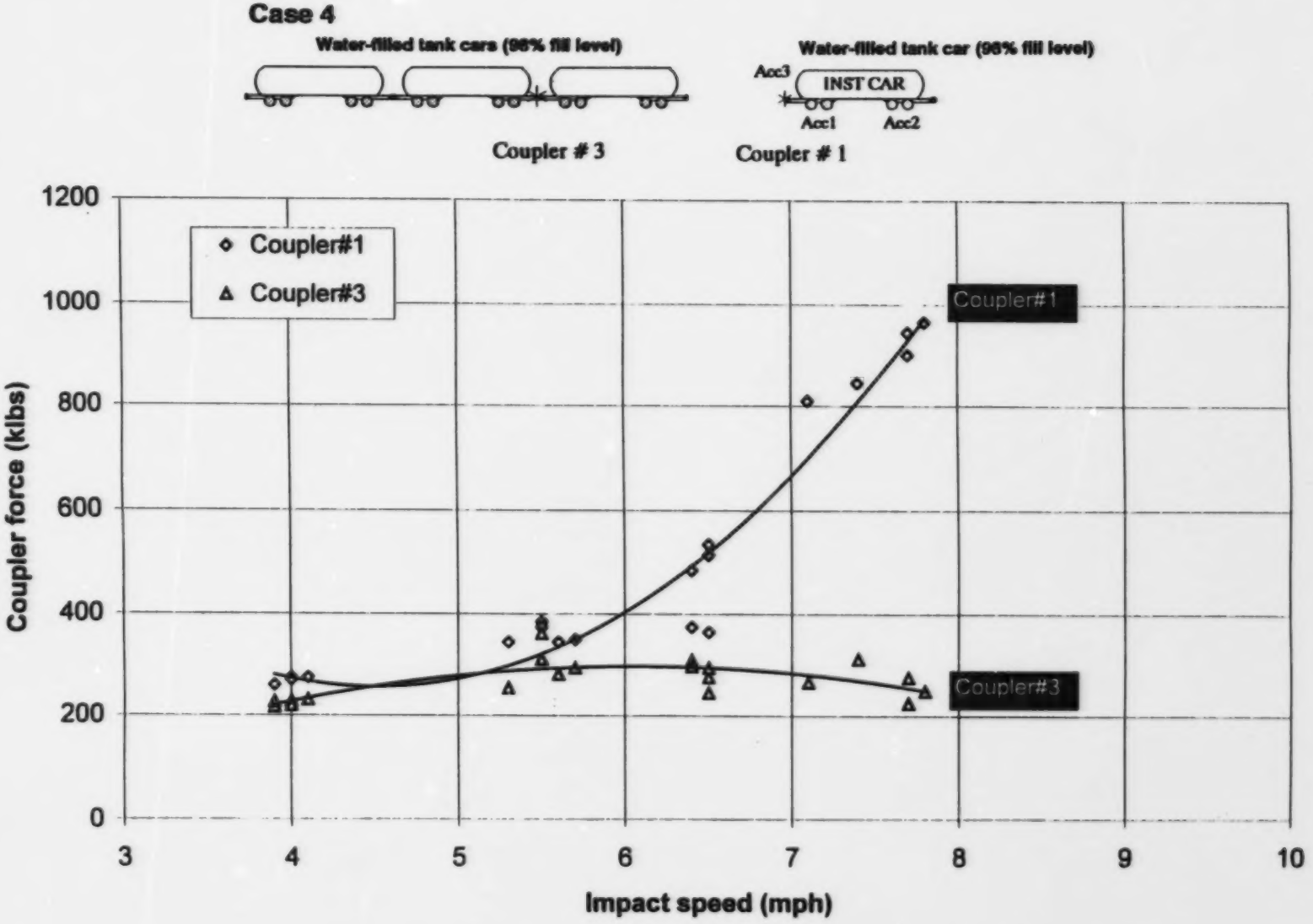


Figure 11. Maximum impact forces at different couplers versus speed for case #4

Table 6: Measured coupler forces and accelerations at different speeds for case #4

Case #4	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	Maximum Coupler Forces #3 (Klbs)	Maximum Accelerations Acc1 (g)	Maximum Accelerations Acc2 (g)	Maximum Accelerations Acc3 (g)
Three loaded tank cars hit one loaded anvil car.	3.9	98%	260	217	3.0	4.0	4.5
	3.9	98%	260	227	4.7	2.6	2.1
	4.1	98%	275	231	8.3	5.8	2.1
	4.0	98%	275	228	5.9	2.8	5.7
	4.0	98%	270	220	5.1	4.1	5.4
	5.7	98%	350	294	7.3	5.9	6.1
	5.6	98%	345	281	8.6	4.1	5.9
	5.5	98%	385	362	4.9	6.7	3.5
	5.3	98%	345	254	6.3	4.1	4.1
	5.5	98%	375	311	7.0	3.7	8.1
	6.4	98%	375	309	8.7	7.4	8.6
	6.5	98%	365	276	17.4	8.4	9.8
	6.4	98%	485	297	17.7	7.7	7.3
	6.5	98%	535	294	21.0	8.1	8.3
	6.5	98%	515	245	13.5	10.7	10.2
	7.1	98%	810	266	15.7	9.2	14.5
	7.4	98%	845	312	19.4	9.3	11.5
	7.7	98%	945	276	10.4	7.6	13.9
	7.7	98%	900	225	7.5	11.1	8.7
	7.8	98%	965	249	18.2	11.4	22.5

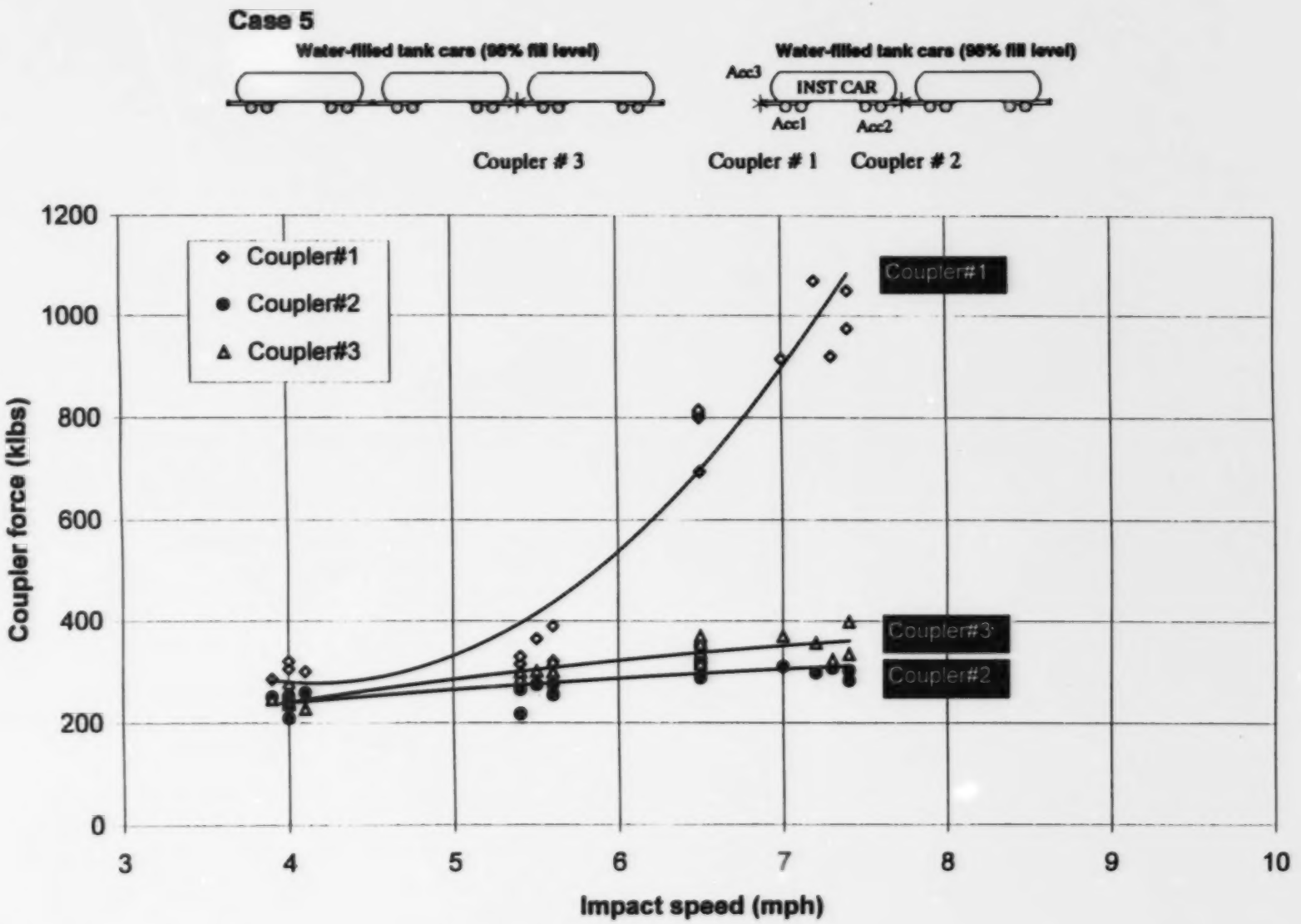


Figure 12. Maximum impact forces at different couplers versus speed for case #5

Table 7: Measured coupler forces and accelerations at different speeds for case #5

Case #5	Impact Speed	Fill Level of Loaded Car	Maximum Coupler Forces			Maximum Accelerations		
			#1	#2	#3	Acc1	Acc2	Acc3
	(mph)		(Klbs)	(Klbs)	(Klbs)	(g)	(g)	(g)
Three loaded tank cars hit two loaded anvil cars.	3.9	98%	285	250	246	4.0	8.7	3.3
	4.1	98%	300	259	227	6.8	13.1	1.8
	4.0	98%	270	247	236	7.0	13.8	6.8
	4.0	98%	305	209	255	5.3	19.2	6.0
	4.0	98%	320	252	241	4.8	13.8	6.3
	5.4	98%	315	218	286	7.1	10.3	4.8
	5.6	98%	320	255	299	5.5	18.7	7.1
	5.5	98%	365	275	301	5.4	20.7	12.7
	5.4	98%	330	265	299	4.2	23.4	5.0
	5.6	98%	390	275	320	5.7	15.6	6.2
	6.5	98%	800	313	328	11.2	14.1	10.8
	6.5	98%	695	323	337	17.5	20.1	9.4
	6.5	98%	810	335	315	14.6	10.8	13.8
	6.5	98%	805	288	355	10.0	14.5	11.4
	6.5	98%	815	350	370	22.8	11.7	16.7
	7.4	98%	975	302	334	10.0	24.7	7.9
	7.4	98%	1050	283	398	14.1	22.5	9.0
	7.3	98%	920	307	323	17.6	24.5	8.0
	7.2	98%	1070	298	356	20.1	20.3	11.0
	7.0	98%	915	310	370	18.0	24.7	12.5

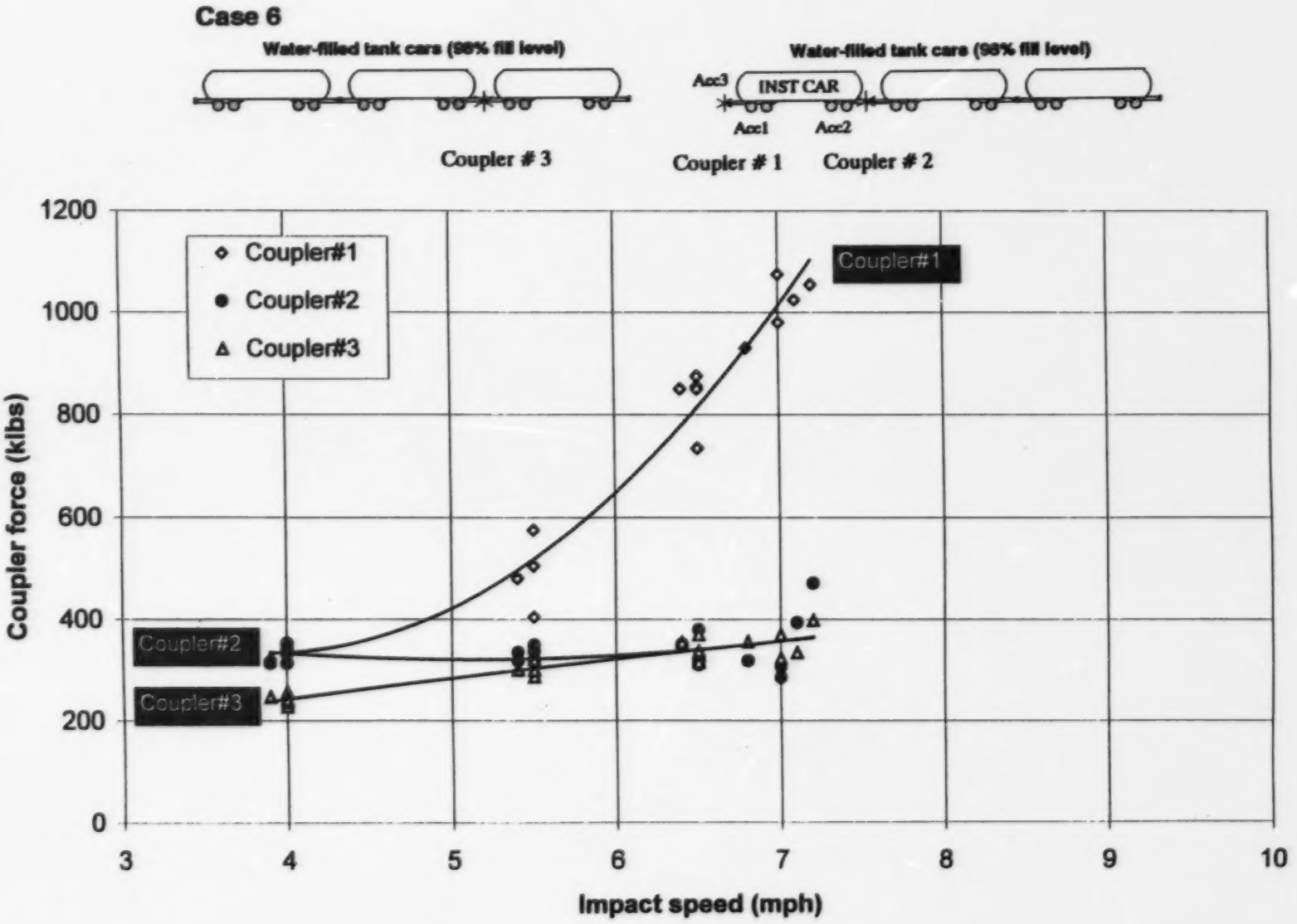


Figure 13. Maximum impact forces at different couplers versus speed for case #6

Table 8: Measured coupler forces and accelerations at different speeds for case #6

Case #6	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	#2 (Klbs)	#3 (Klbs)	Maximum Accelerations Acc1 (g)	Acc2 (g)	Acc3 (g)
Three loaded tank cars hit three loaded anvil cars.	3.9	98%	320	313	270	8.8	9.6	2.5
	4.0	98%	340	332	273	4.1	8.7	6.8
	4.0	98%	340	344	299	4.8	8.4	7.4
	4.0	98%	340	313	287	7.9	8.7	4.6
	4.0	98%	320	353	350	6.3	7.7	3.4
	5.5	98%	505	319	393	10.9	22.3	11.6
	5.4	98%	480	318	319	12.0	13.6	11.5
	5.4	98%	480	335	330	11.0	9.1	8.7
	5.5	98%	575	337	339	14.1	13.0	8.9
	5.5	98%	405	350	318	12.5	15.1	8.9
	6.5	98%	935	380	412	18.0	15.9	19.8
	6.5	98%	875	310	298	15.5	23.2	20.1
	6.5	98%	855	317	407	21.4	19.1	15.9
	6.4	98%	850	351	376	13.8	23.6	16.3
	6.5	98%	850	320	335	21.9	18.9	17.6
	7.1	98%	1025	394	378	18.3	22.1	16.0
	7.2	98%	1055	471	322	21.5	25.9	16.6
	7.0	98%	1075	285	334	18.9	21.5	11.5
	6.8	98%	930	318	302	16.4	21.7	13.1
	7.0	98%	980	307	328	15.4	22.1	15.9

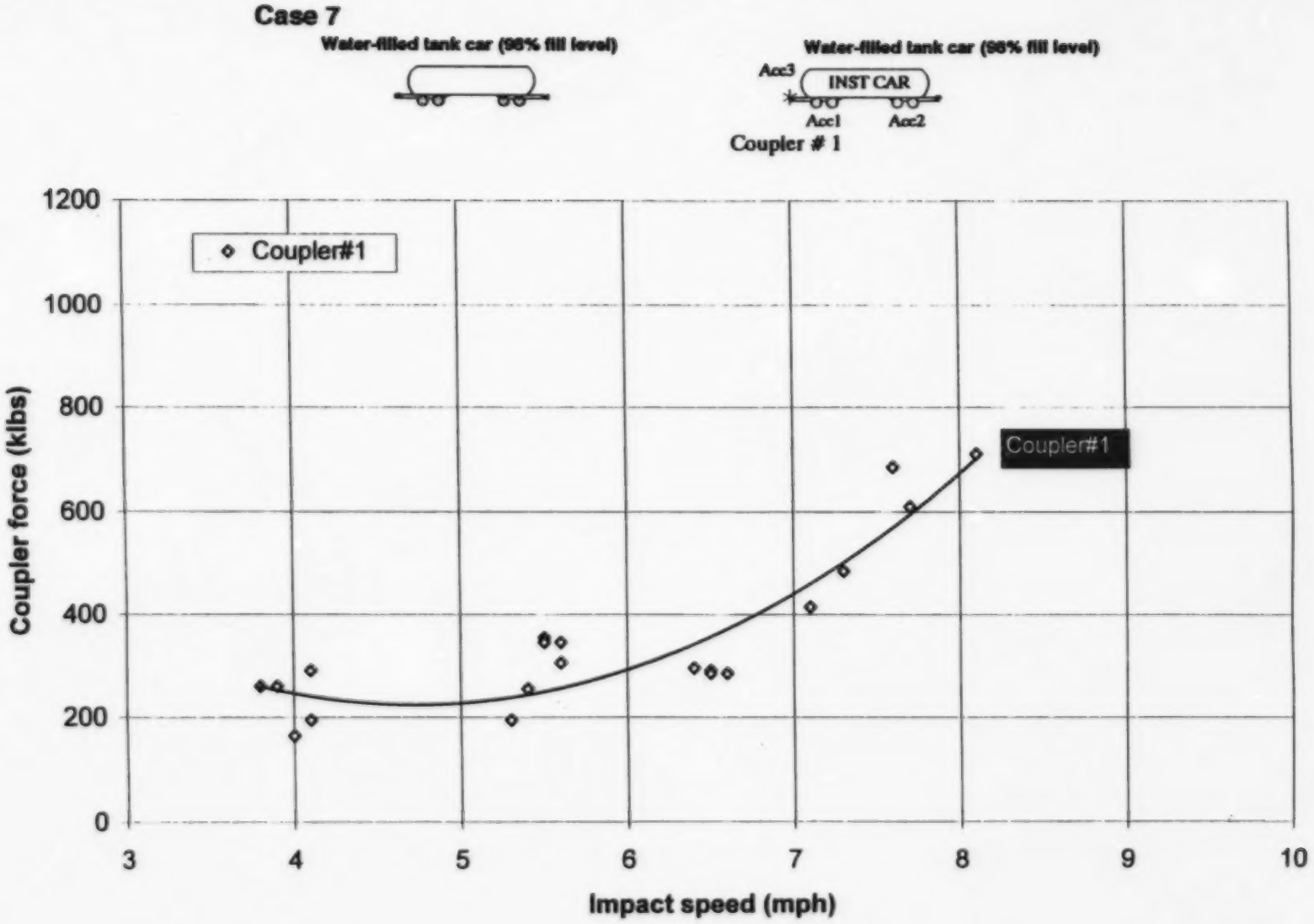


Figure 14. Maximum impact forces at different couplers versus speed for case #7

Table 9: Measured coupler forces and accelerations at different speeds for case #7

Case #7	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Kibs)	Maximum Accelerations Acc1 (g)	Acc2 (g)	Acc3 (g)
One loaded tank car hits one loaded anvil car.	3.8	98%	260	3.9	7.1	5.7
	4.1	98%	195	9.0	6.2	4.9
	3.9	98%	260	5.8	3.6	7.0
	4.0	98%	165	2.4	3.1	3.3
	4.1	98%	290	5.7	9.6	7.1
	5.6	98%	305	5.4	5.6	10.8
	5.6	98%	345	9.3	6.4	8.2
	5.5	98%	355	4.4	4.5	4.7
	5.4	98%	255	4.8	6.6	7.4
	5.5	98%	345	6.3	5.7	6.6
	6.6	98%	285	8.4	12.4	14.4
	6.5	98%	290	8.4	9.1	11.8
	6.5	98%	285	5.2	11.4	12.0
	6.4	98%	295	4.4	12.1	11.2
	6.4	98%	295	2.2	14.9	11.2
	7.1	98%	415	6.7	10.2	14.4
	7.3	98%	485	10.1	13.5	13.7
	7.7	98%	610	6.9	14.1	12.3
	7.6	98%	685	3.5	15.8	11.8
	8.1	98%	710	10.7	15.9	10.3

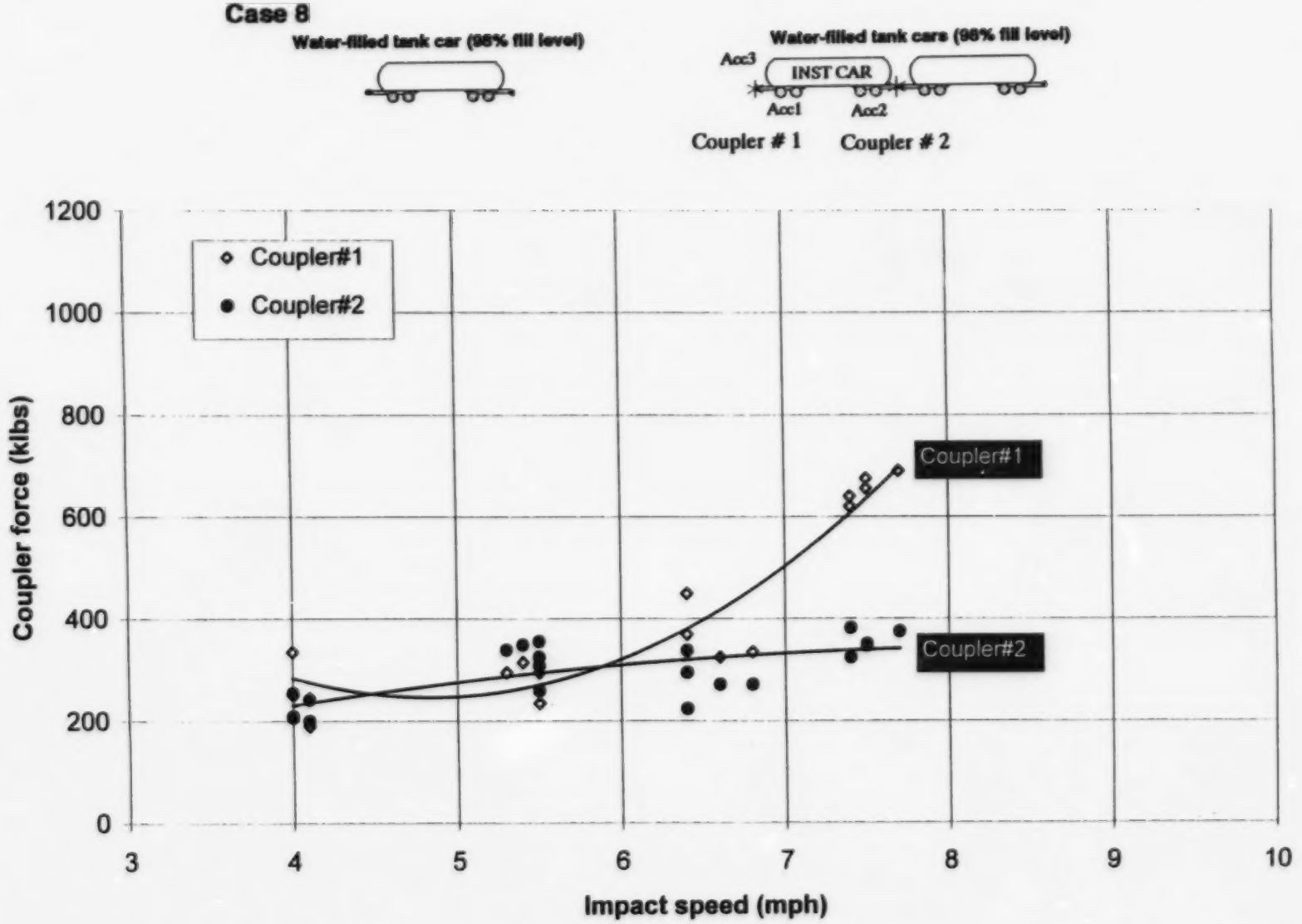


Figure 15. Maximum impact forces at different couplers versus speed for case #8

Table 10: Measured coupler forces and accelerations at different speeds for case #8

Case #8	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	Maximum Coupler Forces #2 (Klbs)	Maximum Accelerations Acc1 (g)	Maximum Accelerations Acc2 (g)	Maximum Accelerations Acc3 (g)
One loaded tank car hits two loaded anvil cars.	4.1	98%	245	200	9.2	15.9	4.8
	4.0	98%	335	207	9.1	15.9	5.2
	4.0	98%	250	209	4.2	11.7	3.1
	4.1	98%	190	242	2.3	13.0	1.8
	4.0	98%	335	255	2.6	17.0	4.2
	5.3	98%	295	339	3.1	19.5	11.2
	5.4	98%	315	349	4.2	15.2	12.9
	5.5	98%	295	308	4.6	19.8	8.6
	5.5	98%	310	356	1.5	19.4	8.1
	5.5	98%	305	325	8.1	12.9	8.9
	6.8	98%	335	272	5.8	17.7	10.6
	6.4	98%	370	338	5.1	22.5	12.4
	6.4	98%	450	295	3.0	14.9	14.3
	6.4	98%	335	224	4.3	18.1	10.5
	6.6	98%	325	272	3.5	19.4	16.1
	7.4	98%	620	382	8.2	18.3	12.7
	7.4	98%	640	325	10.1	17.7	13.1
	7.5	98%	655	347	5.4	19.1	12.0
	7.5	98%	675	351	10.3	22.7	14.8
	7.7	98%	690	375	3.3	25.7	18.4

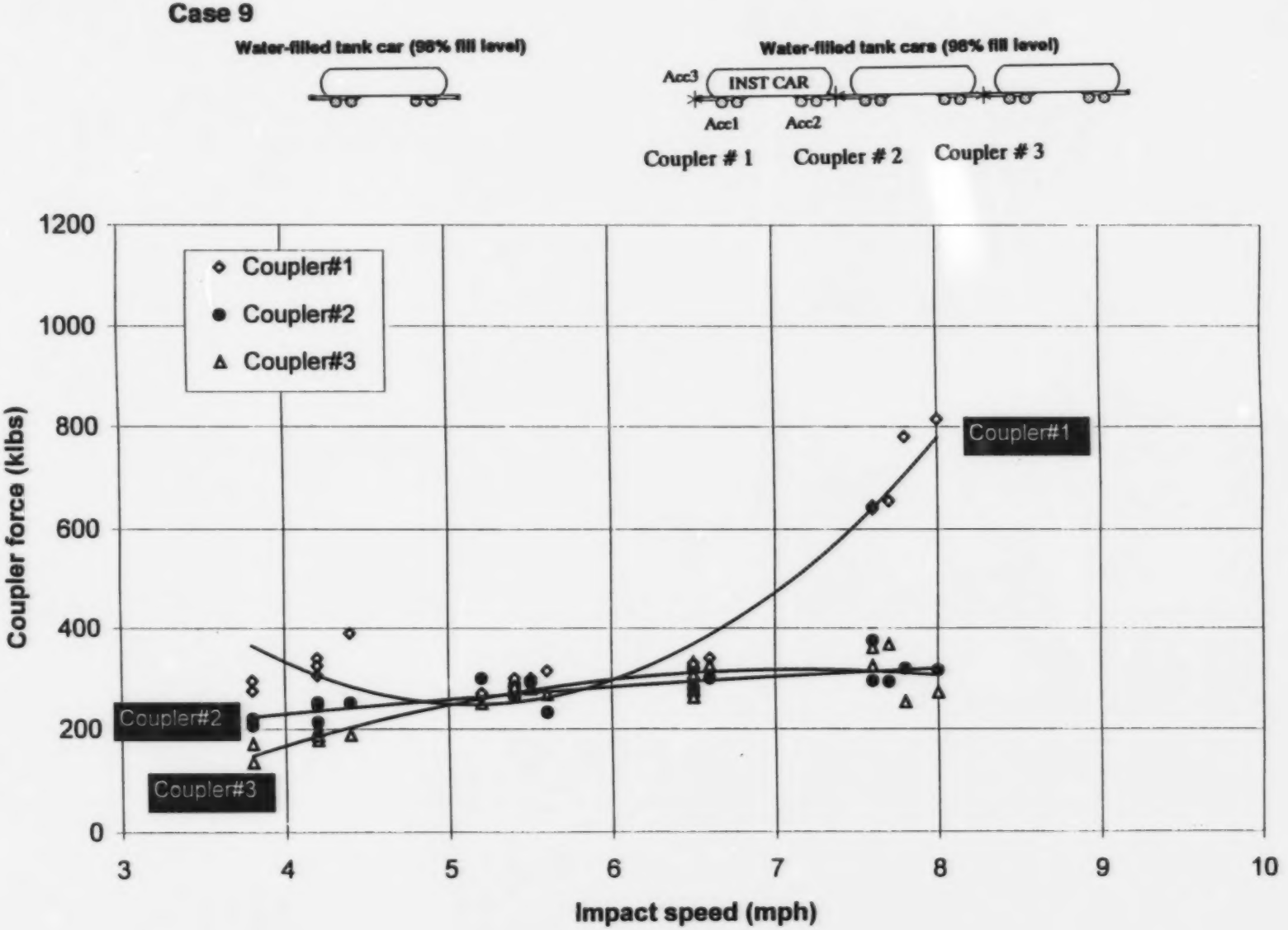


Figure 16. Maximum impact forces at different couplers versus speed for case #9

Table 11: Measured coupler forces and accelerations at different speeds for case #9

Case #9	Impact Speed	Fill Level of Loaded Car	Maximum Coupler Forces			Maximum Accelerations		
			#1	#2	#3	Acc1	Acc2	Acc3
	(mph)		(Klbs)	(Klbs)	(Klbs)	(g)	(g)	(g)
One loaded tank car hits three loaded anvil cars.	3.8	98%	275	220	135	3.1	12.8	4.4
	3.8	98%	295	207	170	3.7	14.2	5.1
	4.4	98%	390	251	188	7.2	11.4	12.5
	4.2	98%	340	247	178	6.3	15.7	7.6
	4.2	98%	305	213	198	8.7	15.3	5.5
	4.2	98%	325	252	187	5.4	12.2	8.5
	5.2	98%	270	300	250	4.9	18.5	5.4
	5.4	98%	290	264	275	6.8	15.8	5.4
	5.4	98%	300	282	283	5.6	12.0	8.3
	5.5	98%	300	292	279	4.0	15.9	7.5
	5.6	98%	315	233	268	10.7	17.3	7.5
	6.6	98%	340	300	325	2.4	16.9	12.3
	6.5	98%	320	282	325	5.1	17.5	10.5
	6.5	98%	320	279	304	3.5	19.3	11.0
	6.5	98%	300	277	331	5.6	21.9	13.9
	6.4	98%	330	320	262	1.3	22.6	11.1
	6.5	98%	320	266	306	3.8	22.1	12.5
	7.6	98%	645	375	360	6.3	15.2	13.3
	7.6	98%	640	295	324	6.8	18.6	17.4
	7.7	98%	655	293	367	8.1	21.8	14.6
	7.8	98%	780	319	253	5.2	31.4	11.9
	8.0	98%	815	316	272	6.0	30.3	13.5

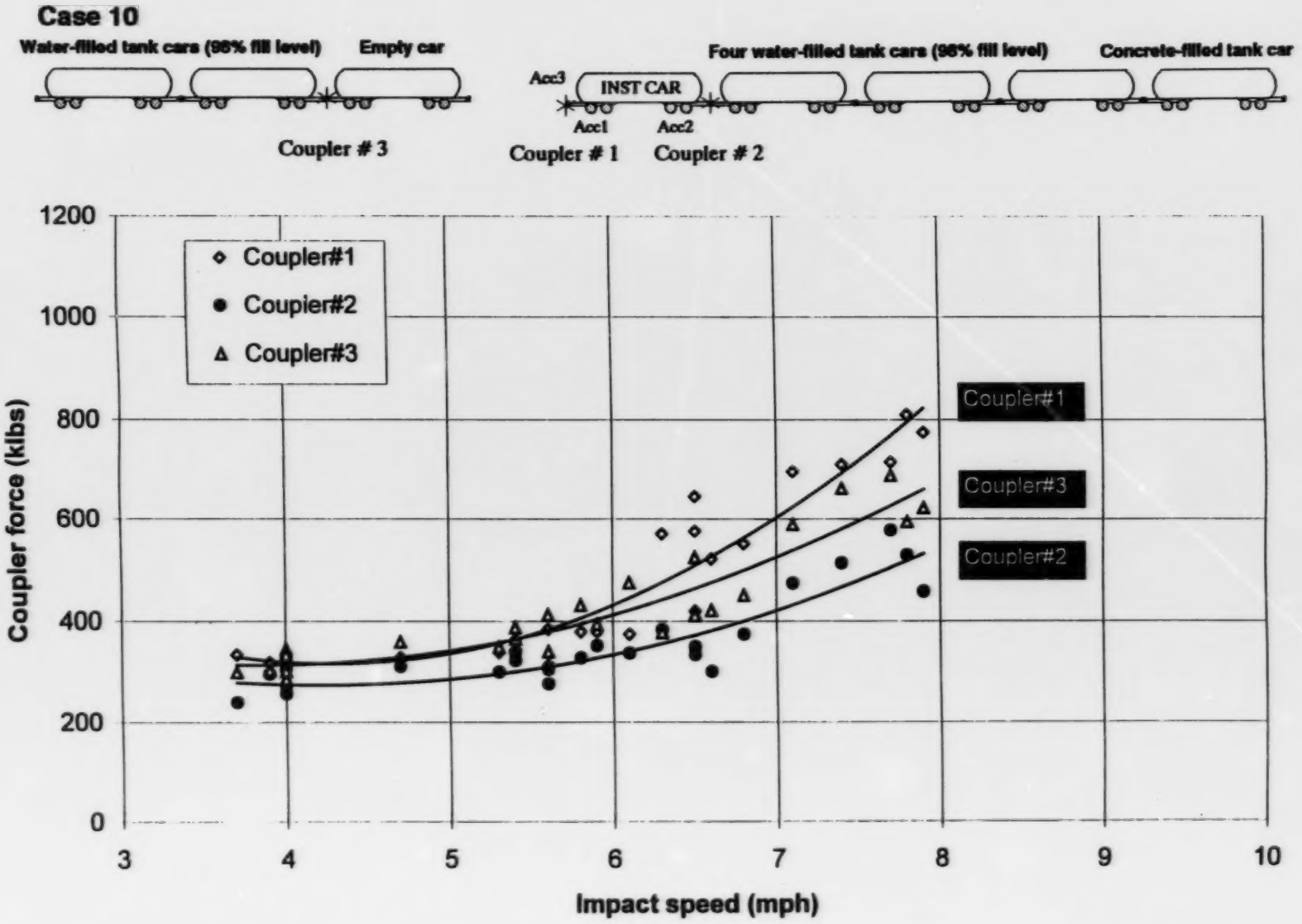


Figure 17. Maximum impact forces at different couplers versus speed for case #10

Table 12: Measured coupler forces and accelerations at different speeds for case #10

Case #10	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	#2 (Klbs)	#3 (Klbs)	Maximum Accelerations Acc1 (g)	Acc2 (g)	Acc3 (g)
Two loaded tank cars and one empty car hit five loaded anvil cars.	3.7	98%	335	240	300	6.0	16.7	6.3
	4.0	98%	335	257	286	3.5	15.0	4.3
	4.0	98%	330	274	346	4.7	17.7	4.0
	4.0	98%	320	260	302	2.9	22.0	4.9
	3.9	98%	320	297	304	5.1	12.3	4.1
	4.0	98%	330	307	334	2.2	17.8	4.4
	4.7	98%	330	312	360	6.1	21.8	6.5
	5.3	98%	340	301	350	2.5	18.0	9.0
	5.6	98%	315	306	341	4.5	23.6	12.3
	5.4	98%	345	324	366	8.3	18.6	11.2
	5.4	98%	365	340	388	4.5	17.6	10.5
	5.6	98%	385	277	412	3.8	21.8	10.4
	5.9	98%	380	353	394	6.7	24.0	15.1
	6.3	98%	570	384	378	4.9	26.3	17.9
	6.5	98%	645	335	414	5.9	27.6	14.5
	6.5	98%	575	351	411	5.6	35.8	16.1
	6.6	98%	520	302	421	6.0	30.6	14.6
	5.8	98%	380	329	431	6.9	24.9	12.3
	6.1	98%	375	338	474	7.6	28.6	11.9
	6.8	98%	550	375	450	6.0	21.2	13.1
	6.5	98%	420	349	523	10.6	28.6	13.2
	7.1	98%	695	473	588	7.7	31.2	13.2
	7.4	98%	710	512	661	11.0	33.1	13.2
	7.7	98%	715	577	687	8.9	27.6	15.6
	7.8	98%	810	528	594	4.4	35.7	12.2
	7.9	98%	775	457	622	9.2	33.7	17.7

Case 11

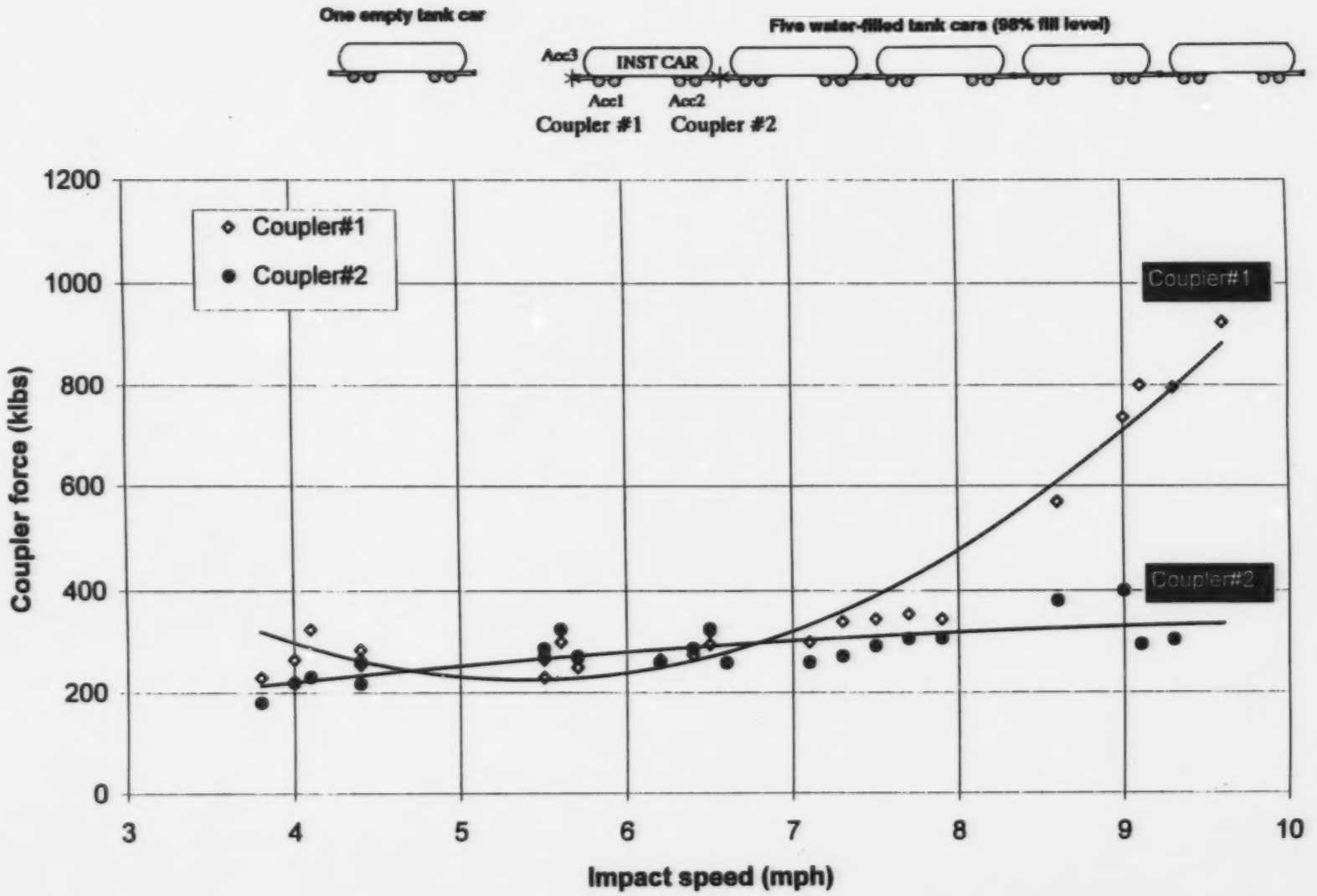


Figure 18. Maximum impact forces at different couplers versus speed for case #11

Table 13: Measured coupler forces and accelerations at different speeds for case #11

Case #11	Impact Speed	Fill Level of Loaded Car	Maximum Coupler Forces		Maximum Accelerations		
			#1	#2	Acc1	Acc2	Acc3
	(mph)		(Klbs)	(Klbs)	(g)	(g)	(g)
One empty tank car hits five loaded anvil cars.	3.8	98%	230	180	12.6	10.5	N/A
	4.4	98%	285	218	2.2	18.2	N/A
	4.4	98%	255	261	4.2	14.1	N/A
	4.0	98%	265	220	4.3	13.0	N/A
	4.1	98%	325	231	8.7	19.0	N/A
	5.7	98%	270	269	10.1	18.3	13.4
	5.5	98%	265	287	1.9	25.4	6.3
	5.6	98%	300	325	6.0	18.1	10.1
	5.7	98%	250	272	3.6	15.0	6.5
	5.5	98%	230	270	4.1	15.5	2.1
	6.2	98%	265	259	6.8	18.8	6.8
	6.4	98%	275	287	5.0	18.3	8.5
	6.5	98%	295	326	6.0	23.0	11.9
	6.6	98%	260	259	8.0	21.9	13.7
	6.5	98%	320	326	7.8	26.6	10.0
	7.1	98%	300	260	5.7	23.8	11.0
	7.3	98%	340	272	14.1	20.2	10.5
	7.5	98%	345	292	3.6	16.9	9.2
	7.7	98%	355	306	6.6	19.3	10.8
	7.9	98%	345	307	16.0	19.7	12.4
	8.6	98%	570	381	5.0	22.6	10.8
	9.0	98%	735	400	5.6	21.7	15.3
	9.1	98%	800	295	4.3	26.3	15.3
	9.3	98%	795	304	5.1	23.5	20.0
	9.6	98%	925	284	3.3	21.2	20.0

Case 12

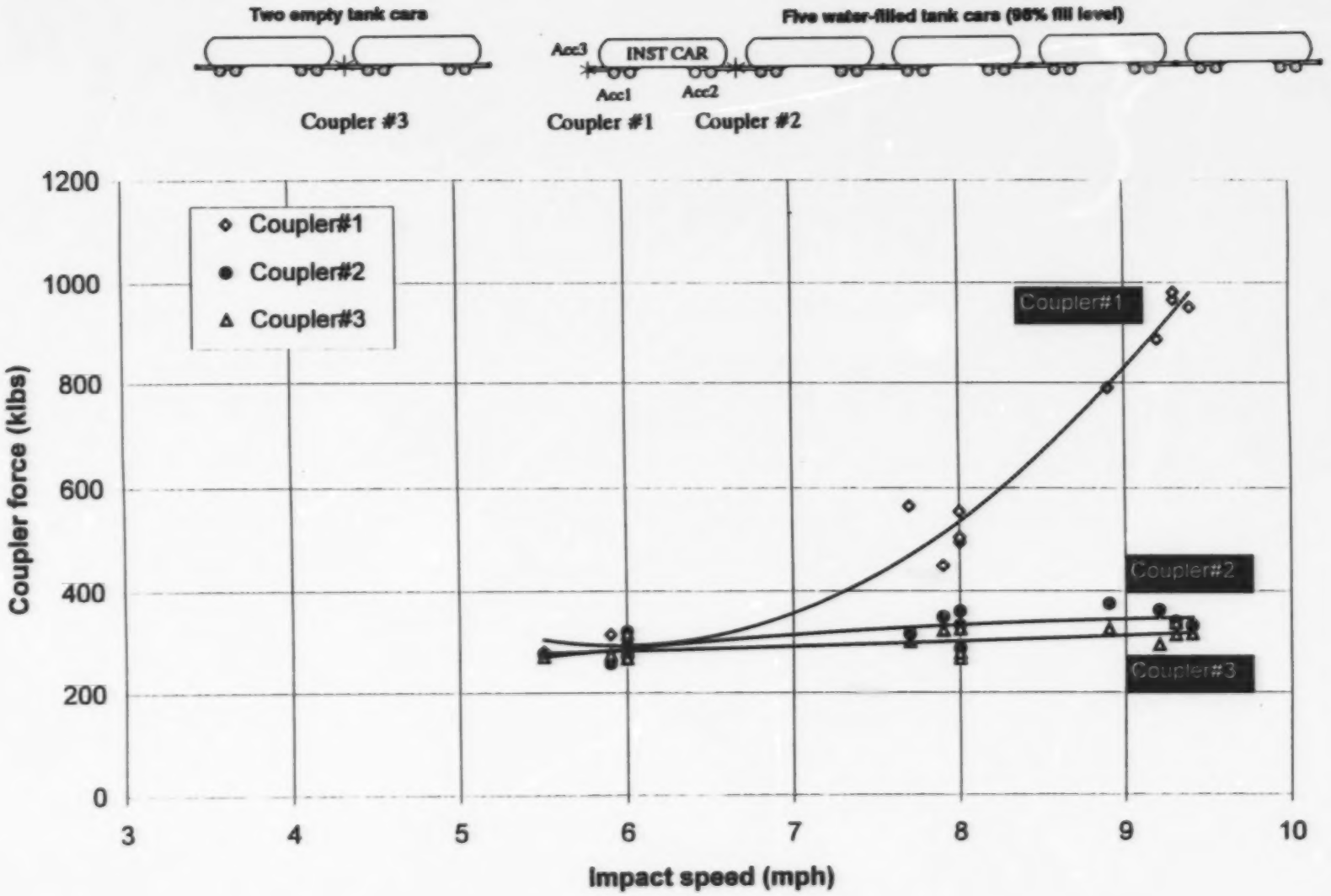


Figure 19. Maximum impact forces at different couplers versus speed for case #12

Table 14: Measured coupler forces and accelerations at different speeds for case #12

Case #12	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	#2 (Klbs)	#3 (Klbs)	Maximum Accelerations Acc1 (g)	Acc2 (g)	Acc3 (g)
Two empty tank cars hit five loaded anvil cars.	5.5	98%	280	277	271	3.1	28.6	11.8
	5.9	98%	315	258	275	4.6	17.0	14.0
	6.0	98%	305	291	281	3.4	21.6	6.3
	6.0	98%	275	320	267	3.1	18.2	6.3
	6.0	98%	305	272	316	N/A	N/A	10.7
	7.7	98%	565	316	300	5.0	15.4	14.4
	8.0	98%	555	332	325	3.4	21.4	10.9
	8.0	98%	495	287	267	12.2	33.9	15.0
	7.9	98%	450	349	322	6.7	26.3	11.9
	8.0	98%	505	360	277	5.2	23.8	14.1
	8.9	98%	790	375	325	5.6	23.1	17.9
	9.2	98%	885	362	294	5.4	26.8	9.4
	9.4	98%	950	331	315	4.3	30.1	14.8
	9.3	98%	965	340	336	5.6	24.5	15.3
	9.3	98%	980	336	313	7.8	35.7	12.4

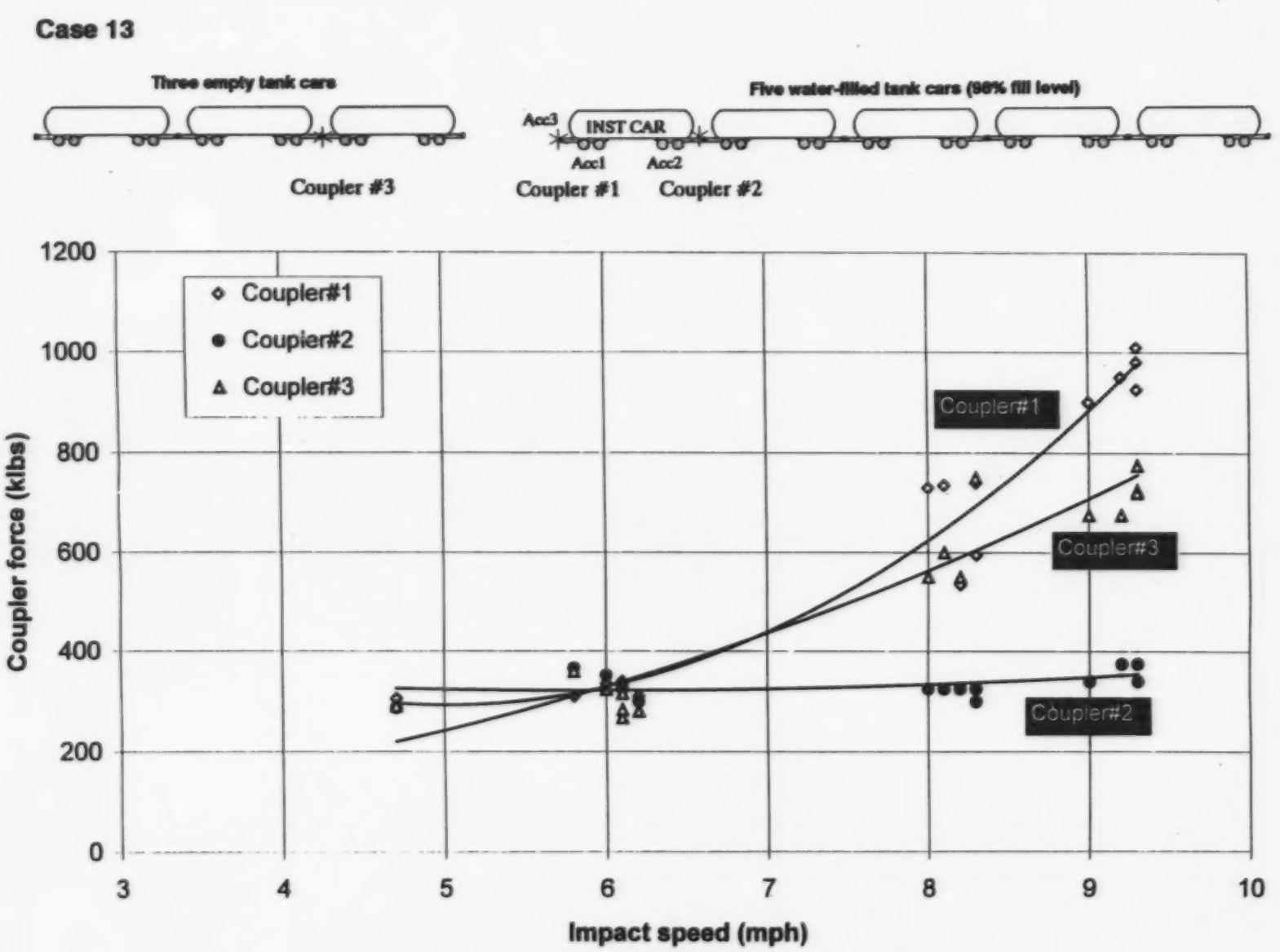


Figure 20. Maximum impact forces at different couplers versus speed for case #13

Table 15: Measured coupler forces and accelerations at different speeds for case #13

Case #13	Impact Speed	Fill Level of Loaded Car	Maximum Coupler Forces			Maximum Accelerations		
			#1	#2	#3	Acc1	Acc2	Acc3
	(mph)		(Kibs)	(Kibs)	(Kibs)	(g)	(g)	(g)
Three empty tank cars hit five loaded anvil cars.	4.7	98%	305	287	290	6.0	26.6	3.4
	5.8	98%	310	366	359	2.1	22.4	9.1
	6.0	98%	335	352	323	2.3	22.8	10.0
	6.1	98%	340	325	315	4.6	21.0	10.2
	6.1	98%	335	336	267	7.7	22.9	10.4
	6.1	98%	340	327	283	4.7	26.7	13.2
	6.2	98%	310	300	280	N/A	27.5	9.3
	8.3	98%	740	325	750	N/A	29.2	11.8
	8.3	98%	595	300	750	N/A	26.0	13.1
	8.2	98%	535	325	550	N/A	23.7	12.0
	8.0	98%	730	325	550	N/A	31.3	11.7
	8.1	98%	735	325	600	N/A	36.7	8.4
	9.0	98%	900	340	675	N/A	48.9	12.2
	9.2	98%	950	375	675	N/A	34.9	18.8
	9.3	98%	1010	375	725	N/A	26.1	19.5
	9.3	98%	925	340	720	N/A	36.7	28.5
	9.3	98%	980	375	775	N/A	32.0	20.6

Case 14

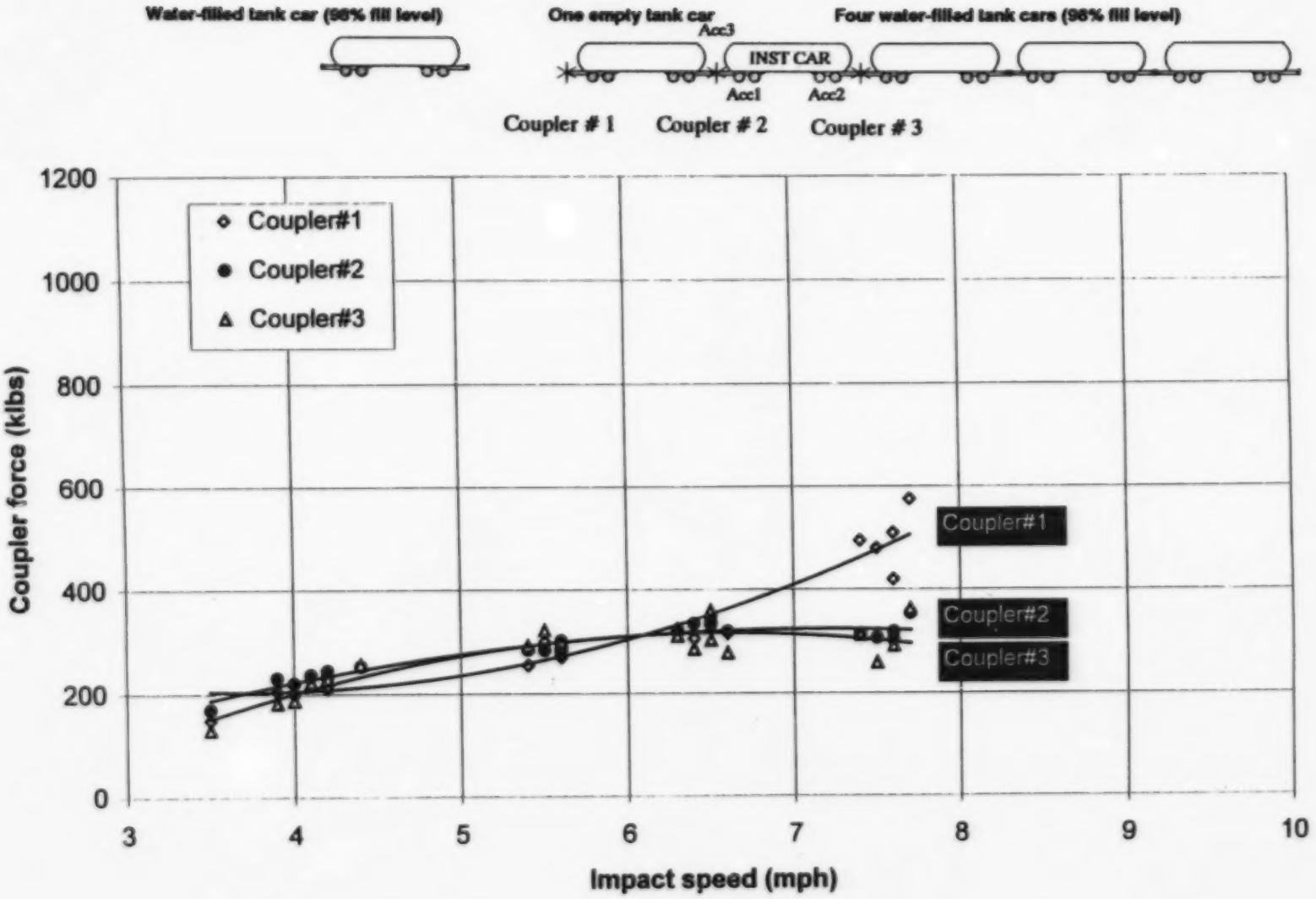


Figure 21. Maximum impact forces at different couplers versus speed for case #14

Table 16: Measured coupler forces and accelerations at different speeds for case #14

Case #14	Impact Speed	Fill Level of Loaded Car	Maximum Coupler Forces			Maximum Accelerations		
			#1	#2	#3	Acc1	Acc2	Acc3
	(mph)		(Klbs)	(Klbs)	(Klbs)	(g)	(g)	(g)
One loaded tank car hits one empty anvil car and four loaded anvil cars.	3.5	98%	150	170	130	3.9	3.6	1.5
	4.4	98%	255	253	257	4.6	8.9	3.7
	4.2	98%	220	245	229	2.0	9.7	1.9
	4.2	98%	210	234	230	3.4	10.6	2.2
	4.1	98%	235	237	222	6.7	6.7	2.1
	4.0	98%	200	221	187	4.4	5.3	1.8
	3.9	98%	205	231	182	6.2	8.8	1.4
	5.6	98%	295	280	300	2.8	19.6	3.0
	5.6	98%	270	302	292	3.3	12.7	6.0
	5.6	98%	275	281	299	6.1	16.2	7.1
	5.4	98%	255	285	292	4.5	18.9	7.1
	5.5	98%	300	284	322	4.3	12.6	5.3
	6.3	98%	325	320	310	4.5	16.8	7.5
	6.4	98%	305	334	285	3.3	24.6	12.2
	6.6	98%	315	319	277	6.5	13.2	7.9
	6.5	98%	335	339	359	8.3	12.9	3.0
	6.5	98%	330	332	302	4.2	19.9	8.8
	7.4	98%	495	314	312	3.5	17.8	9.9
	7.5	98%	480	306	259	5.9	23.0	13.2
	7.6	98%	510	303	291	4.8	19.9	9.8
	7.6	98%	420	318	291	7.9	21.0	7.3
	7.7	98%	575	354	362	3.8	20.0	14.1

Case 15

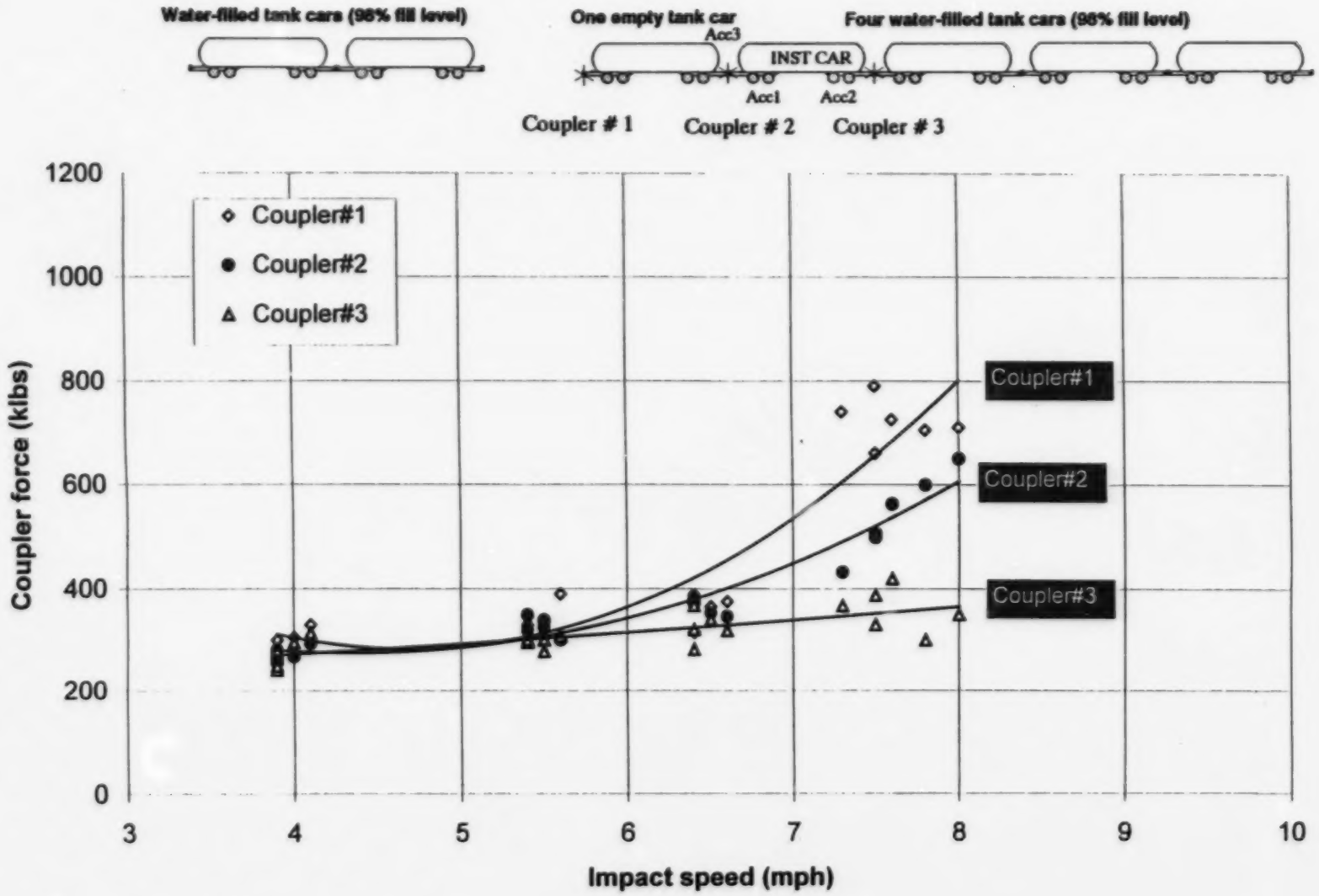
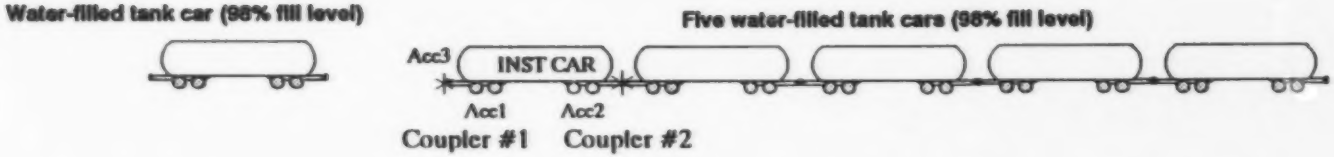


Figure 22. Maximum impact forces at different couplers versus speed for case #15

Table 17: Measured coupler forces and accelerations at different speeds for case #15

Case #15	Impact Speed (mph)	Fill Level of Loaded Car	Maximum Coupler Forces #1 (Klbs)	#2 (Klbs)	#3 (Klbs)	Maximum Accelerations Acc1 (g)	Acc2 (g)	Acc3 (g)
Two loaded tank cars hit one empty anvil car and four loaded anvil cars.	3.9	98%	300	263	240	3.5	21.4	4.9
	3.9	98%	300	280	280	7.4	18.3	2.5
	3.9	98%	275	255	248	5.8	22.1	2.9
	4.0	98%	305	267	294	3.2	19.3	2.4
	4.1	98%	330	293	313	5.5	22.8	2.8
	5.5	98%	335	340	300	3.2	18.4	10.8
	5.5	98%	340	325	277	7.1	17.5	7.5
	5.6	98%	390	300	307	3.2	18.0	11.7
	5.5	98%	340	337	300	4.7	23.3	15.8
	5.4	98%	330	319	295	3.3	26.7	9.0
	5.4	98%	345	350	300	5.0	20.5	8.0
	6.4	98%	370	385	367	4.6	28.5	14.3
	6.4	98%	315	372	281	7.2	25.0	13.3
	6.4	98%	370	378	320	5.0	24.9	15.8
	6.6	98%	375	346	318	12.2	21.8	13.7
	6.5	98%	365	353	340	5.6	31.8	11.9
	7.5	98%	660	500	330	15.1	29.4	11.1
	7.3	98%	740	433	367	9.6	29.1	13.3
	7.5	98%	790	507	387	5.2	32.7	14.2
	7.6	98%	725	563	420	4.6	37.6	12.4
	7.8	98%	705	600	300	12.8	36.8	17.4
	8.0	98%	710	650	350	9.0	41.7	13.8

Case 1



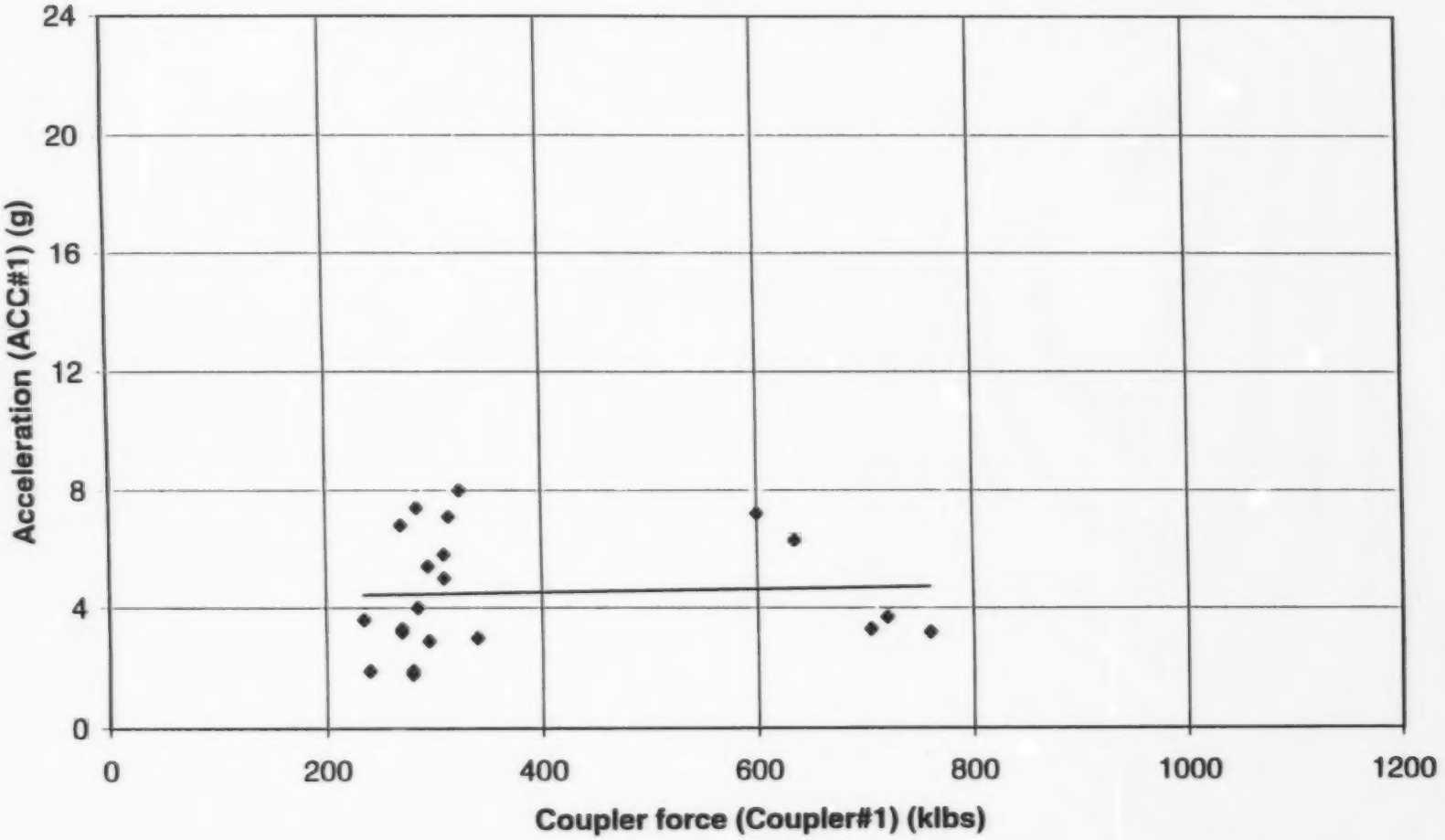
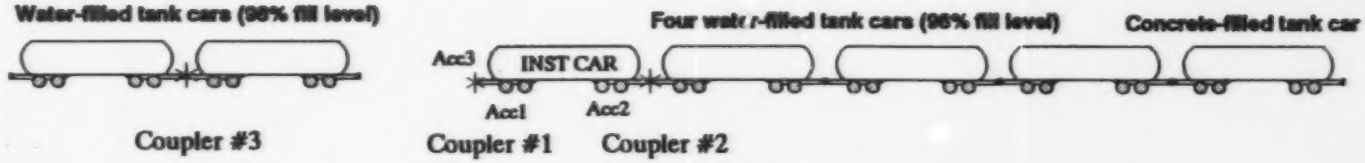


Figure 23. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 1

Case 2



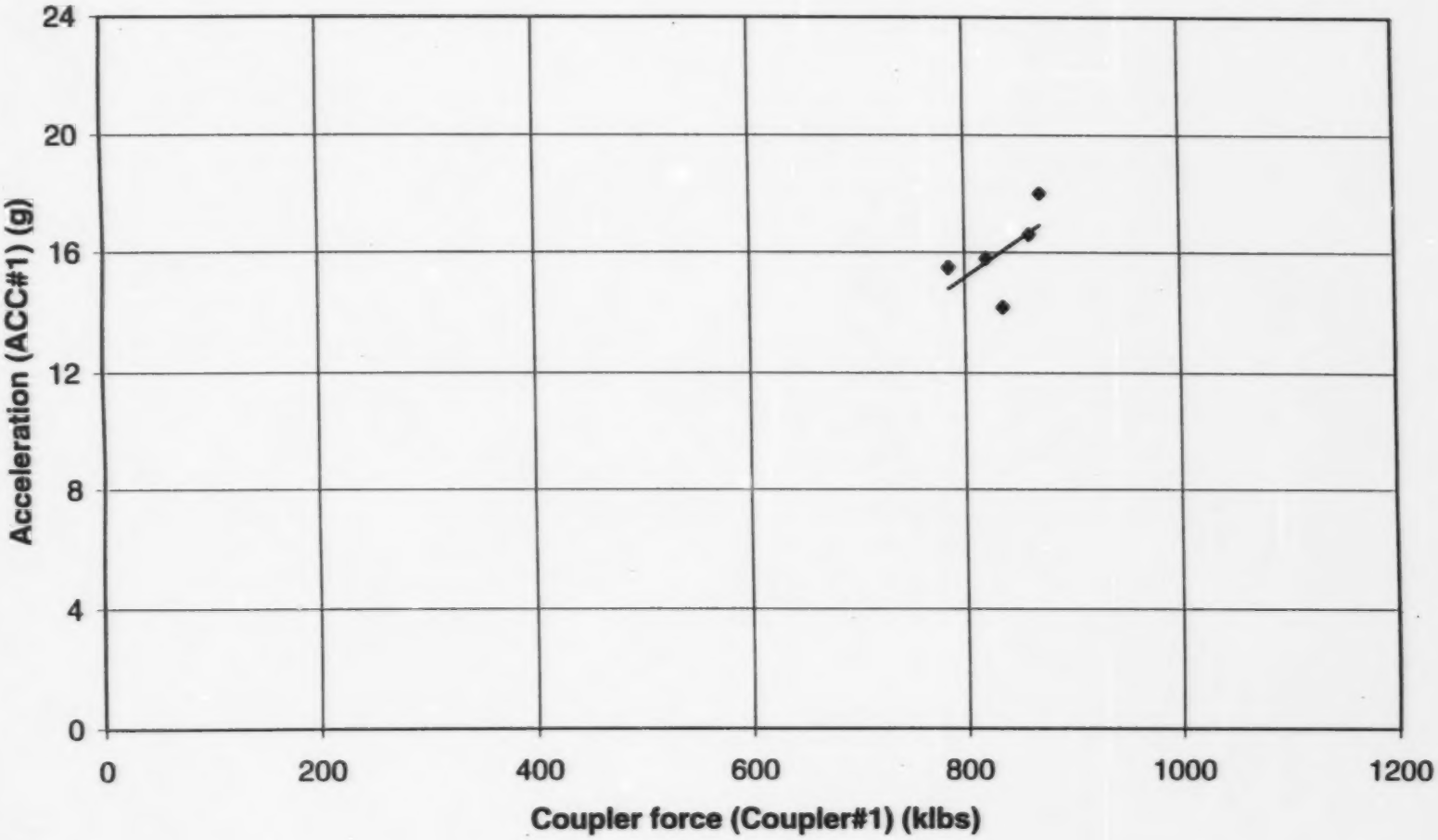


Figure 24. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 2

Case 3

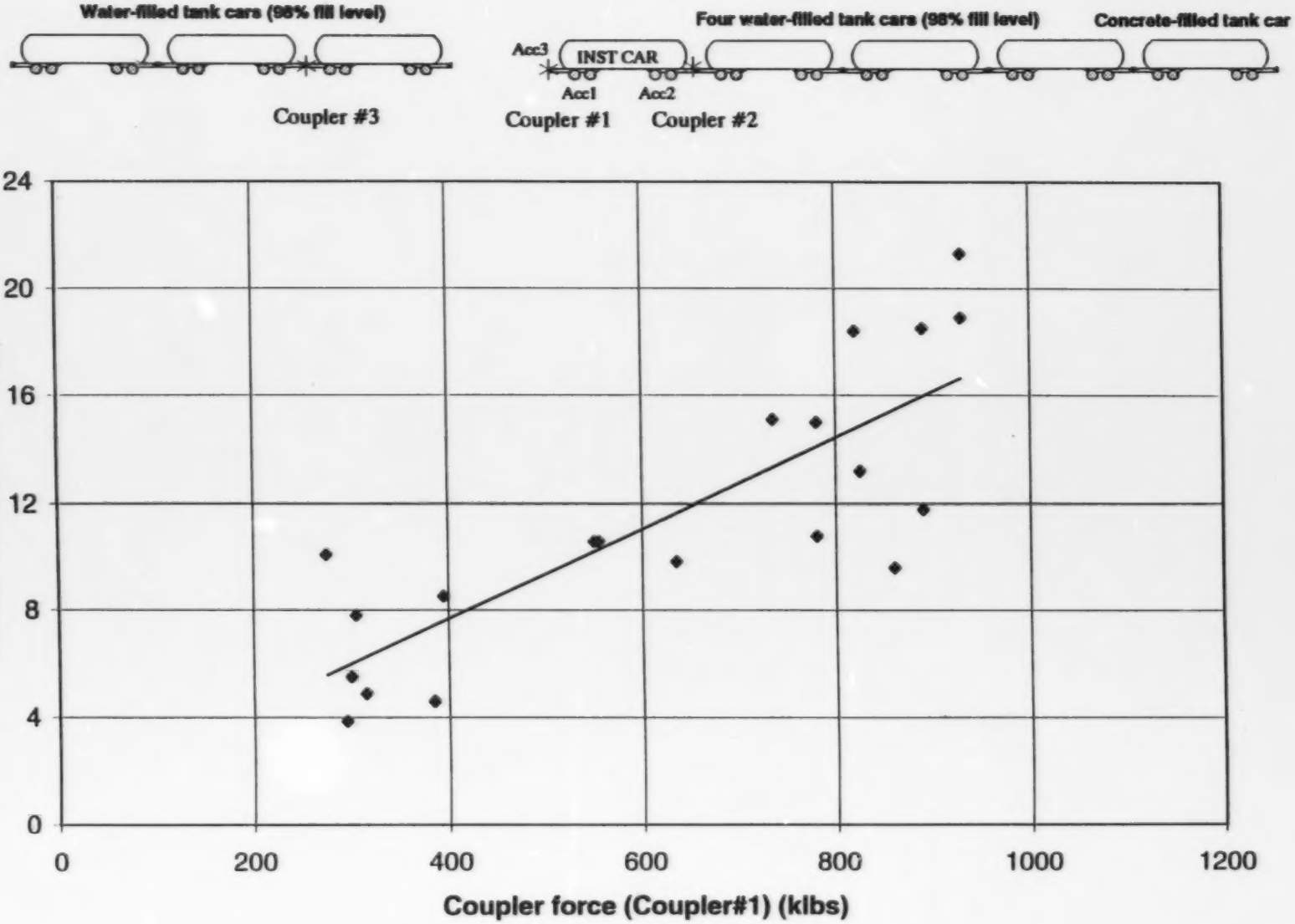
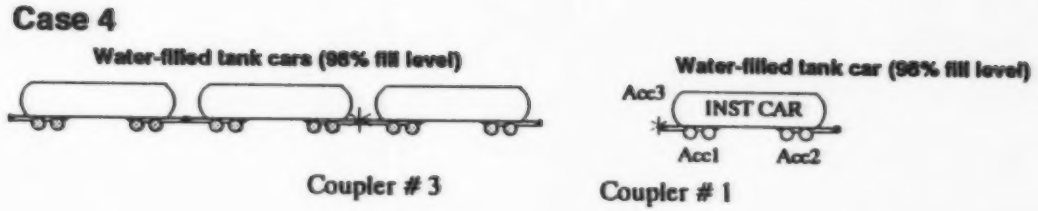


Figure 25. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 3



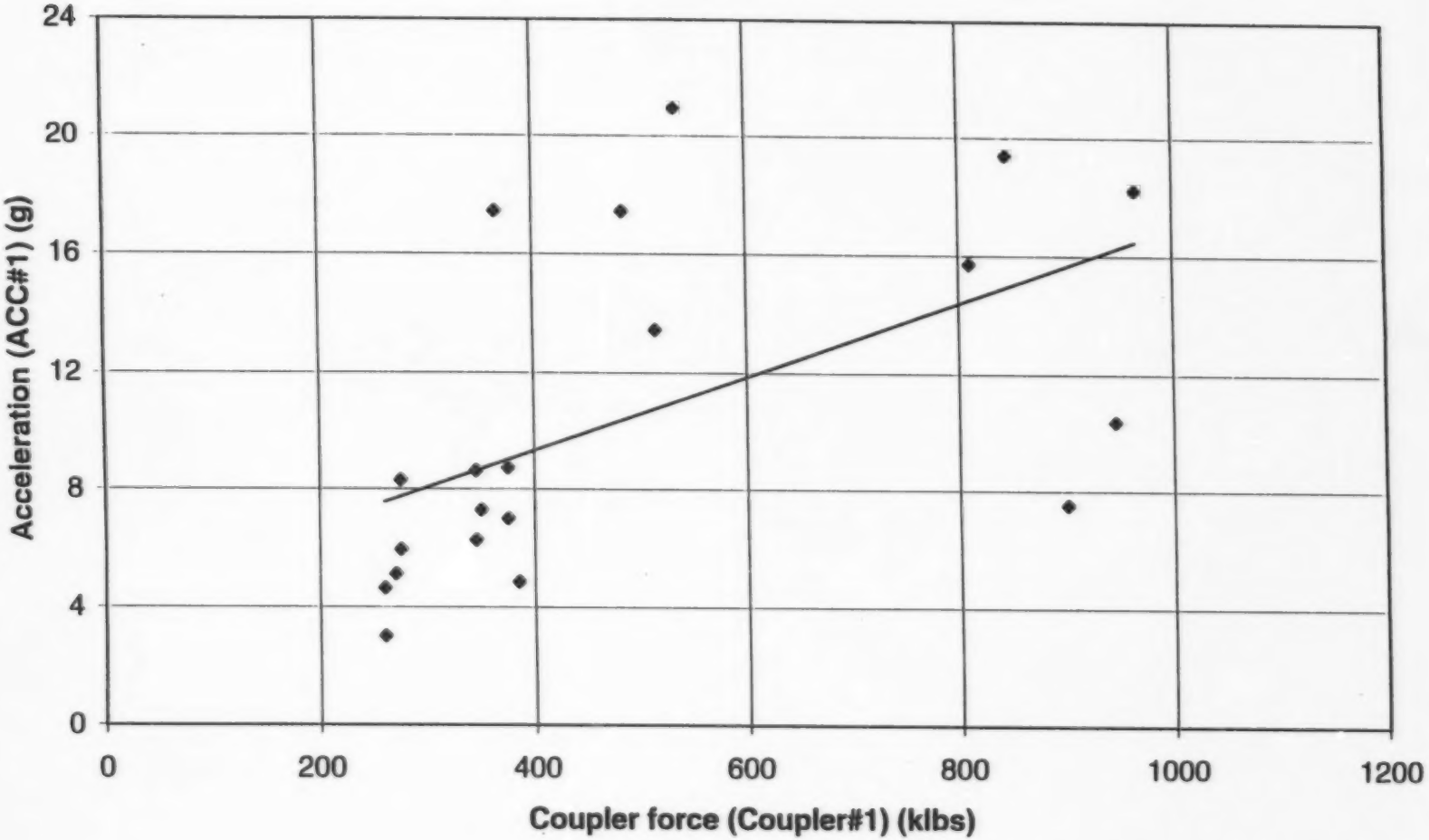


Figure 26. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 4

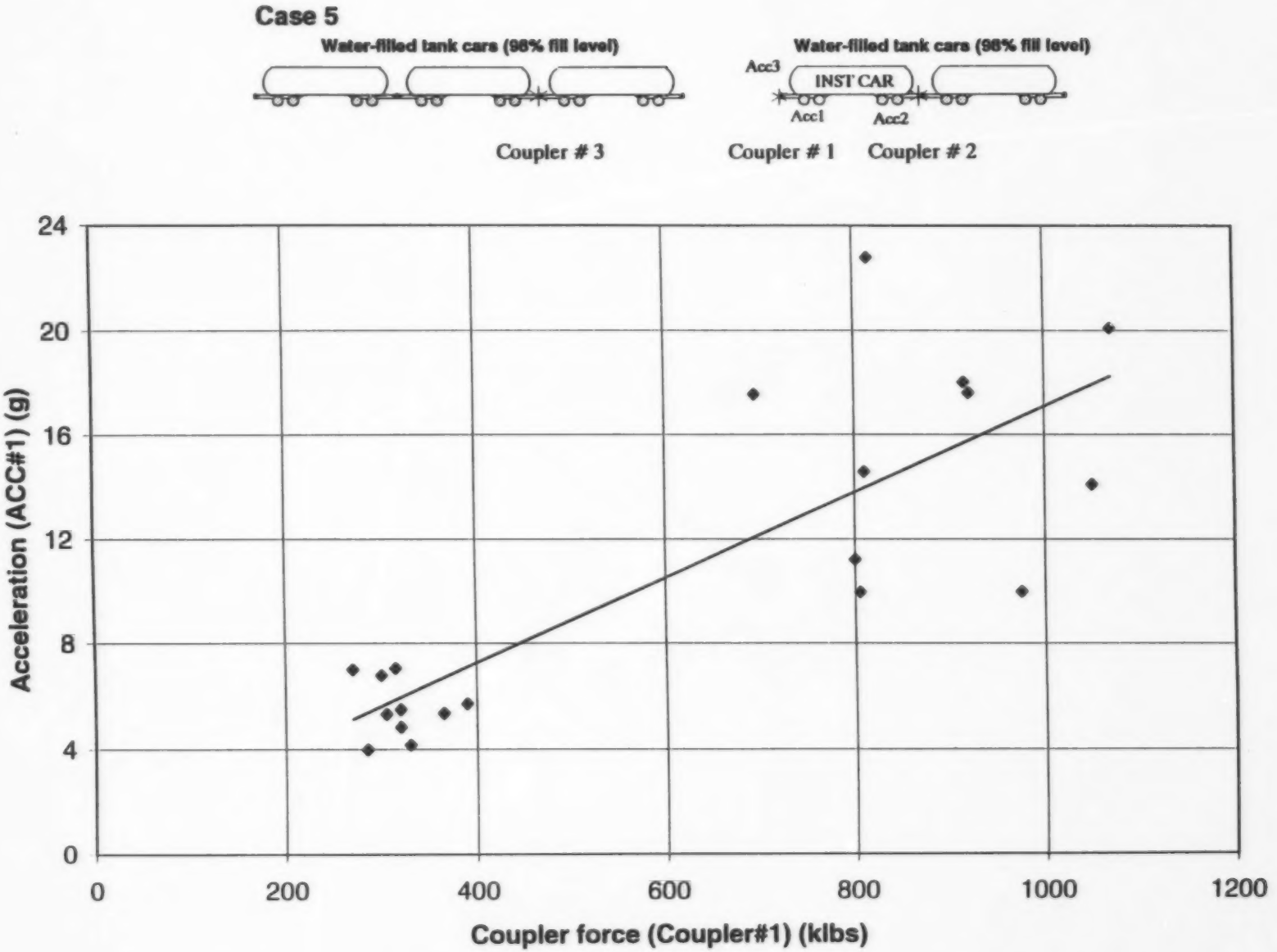


Figure 27. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 5

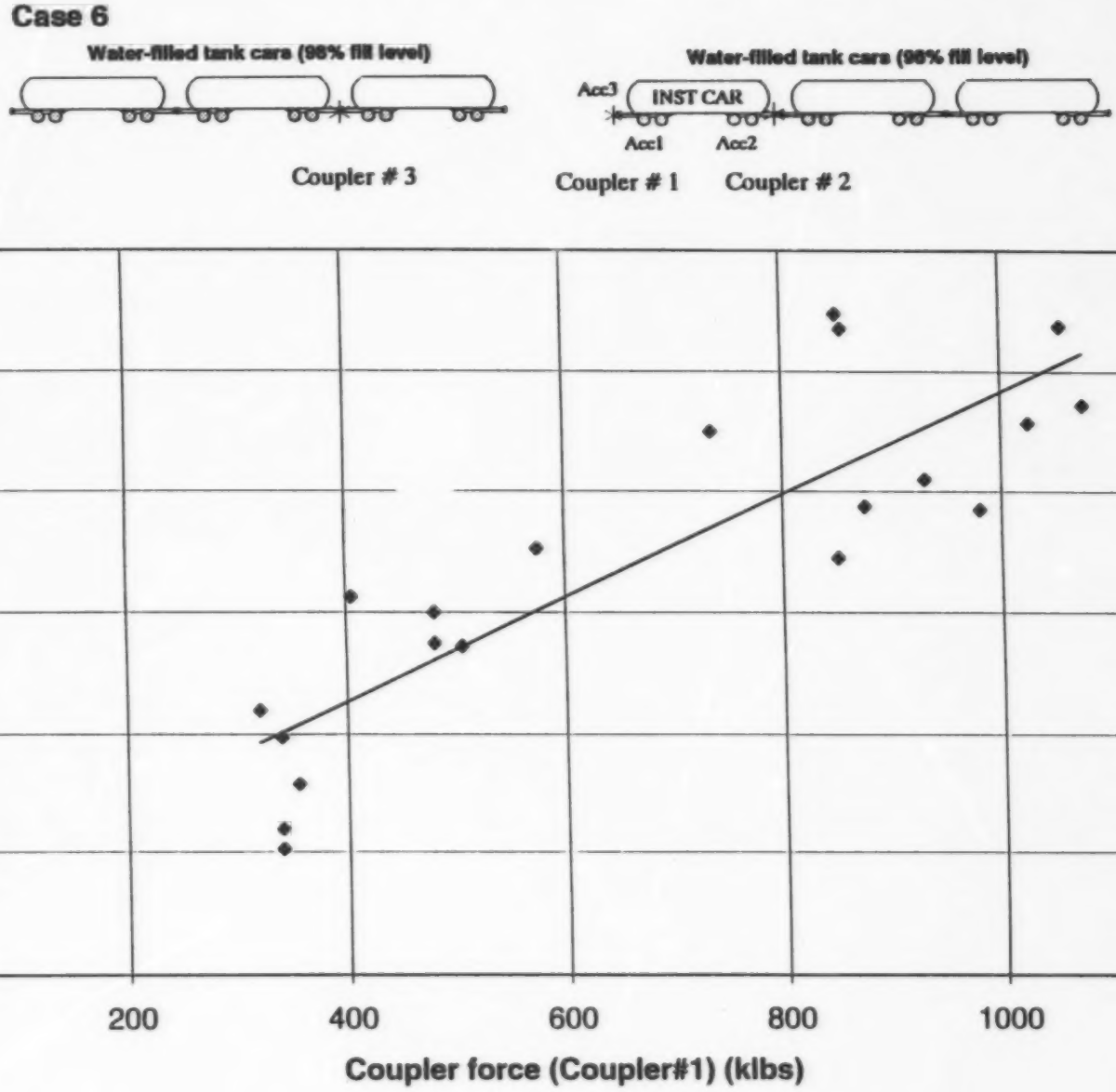


Figure 28. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 6

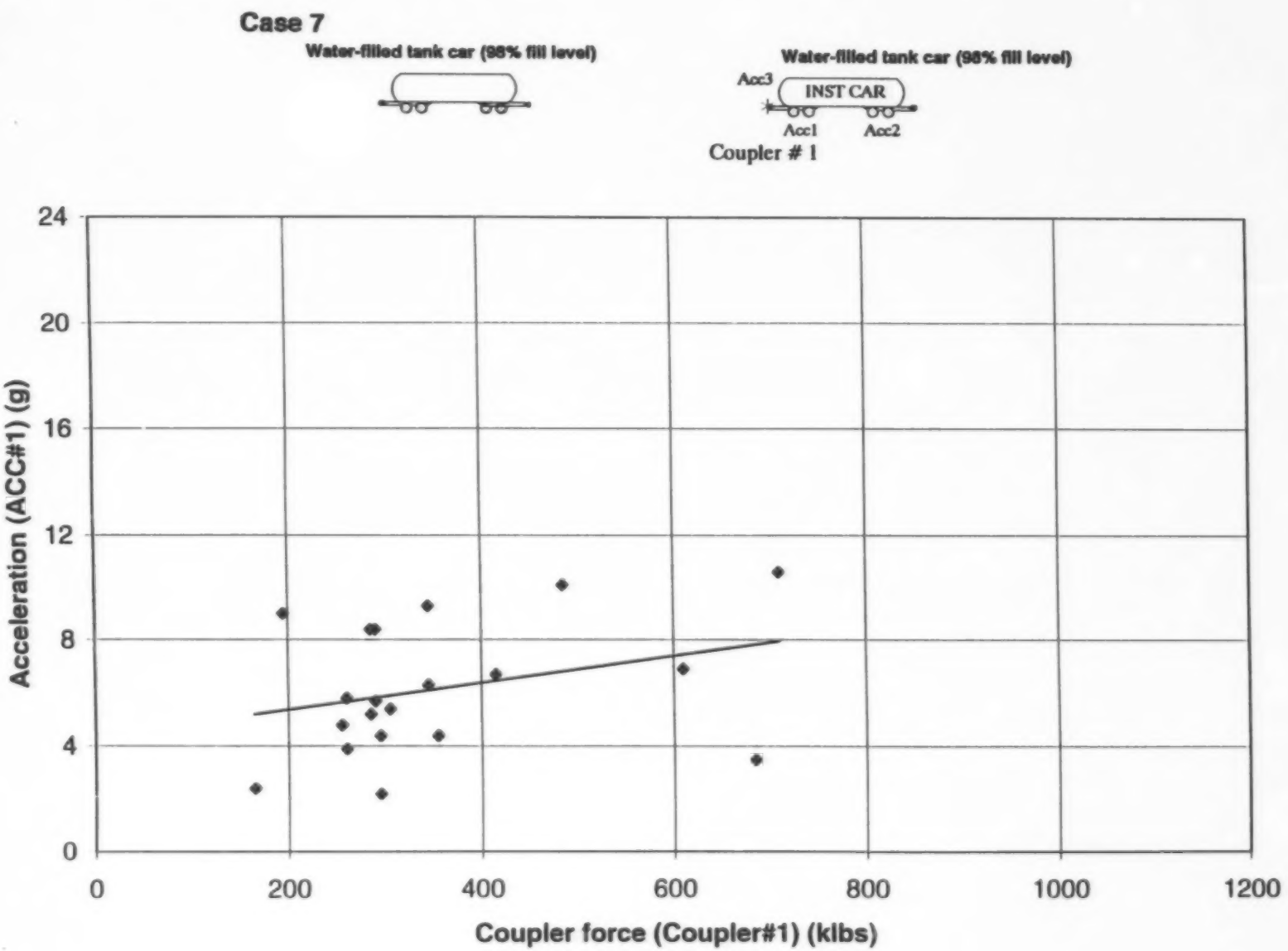


Figure 29. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 7

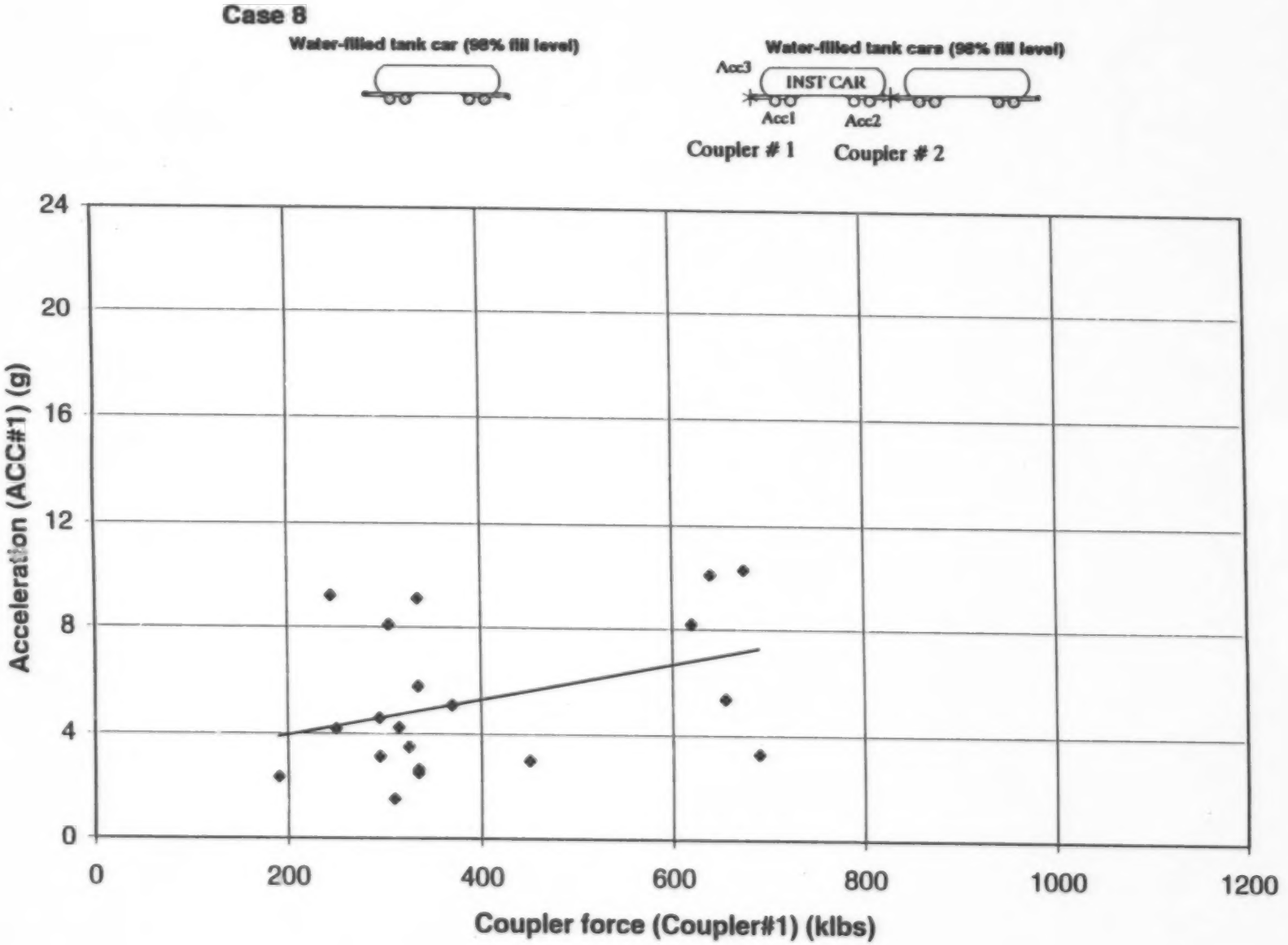


Figure 30. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 8

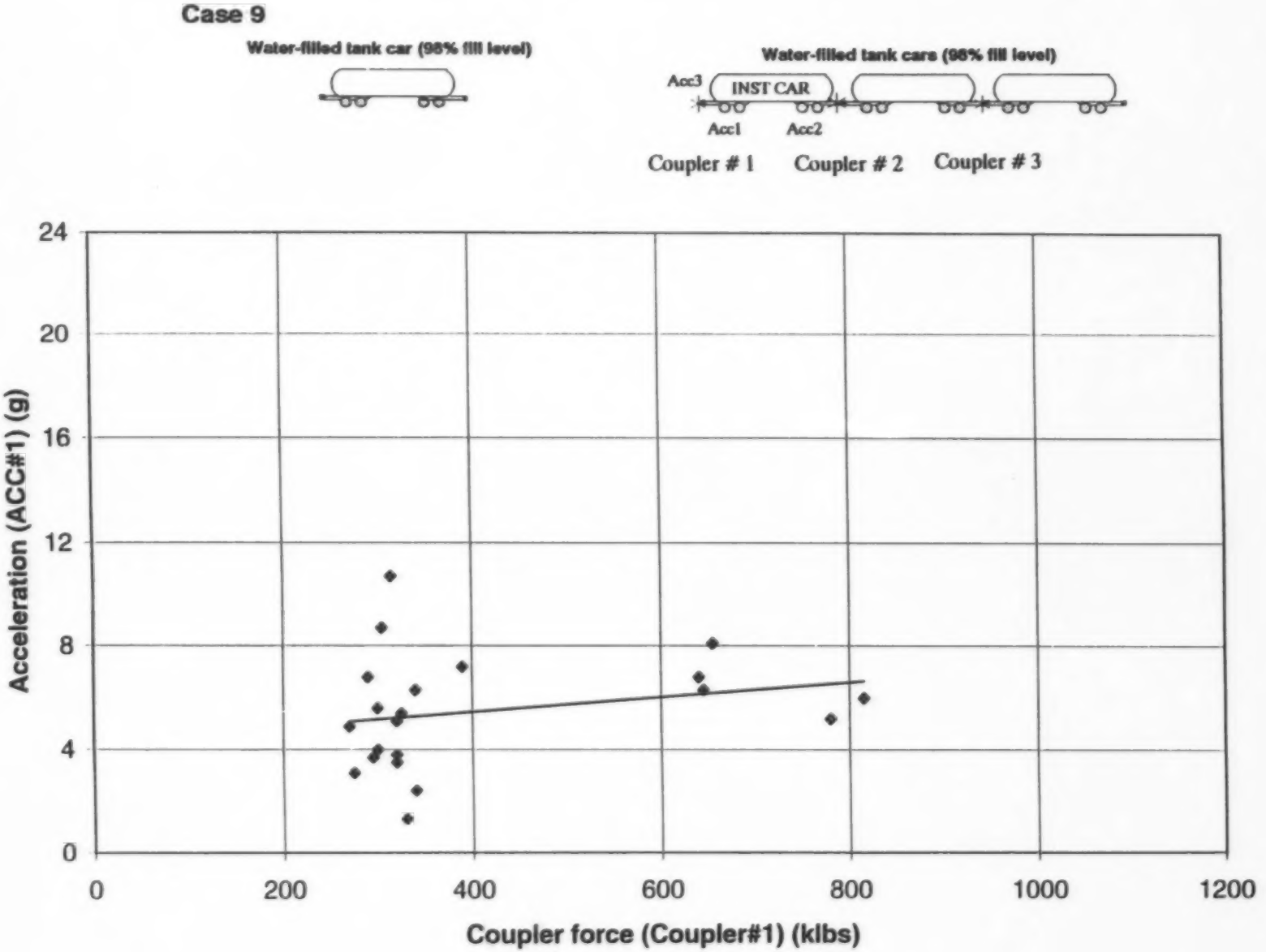


Figure 31. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 9

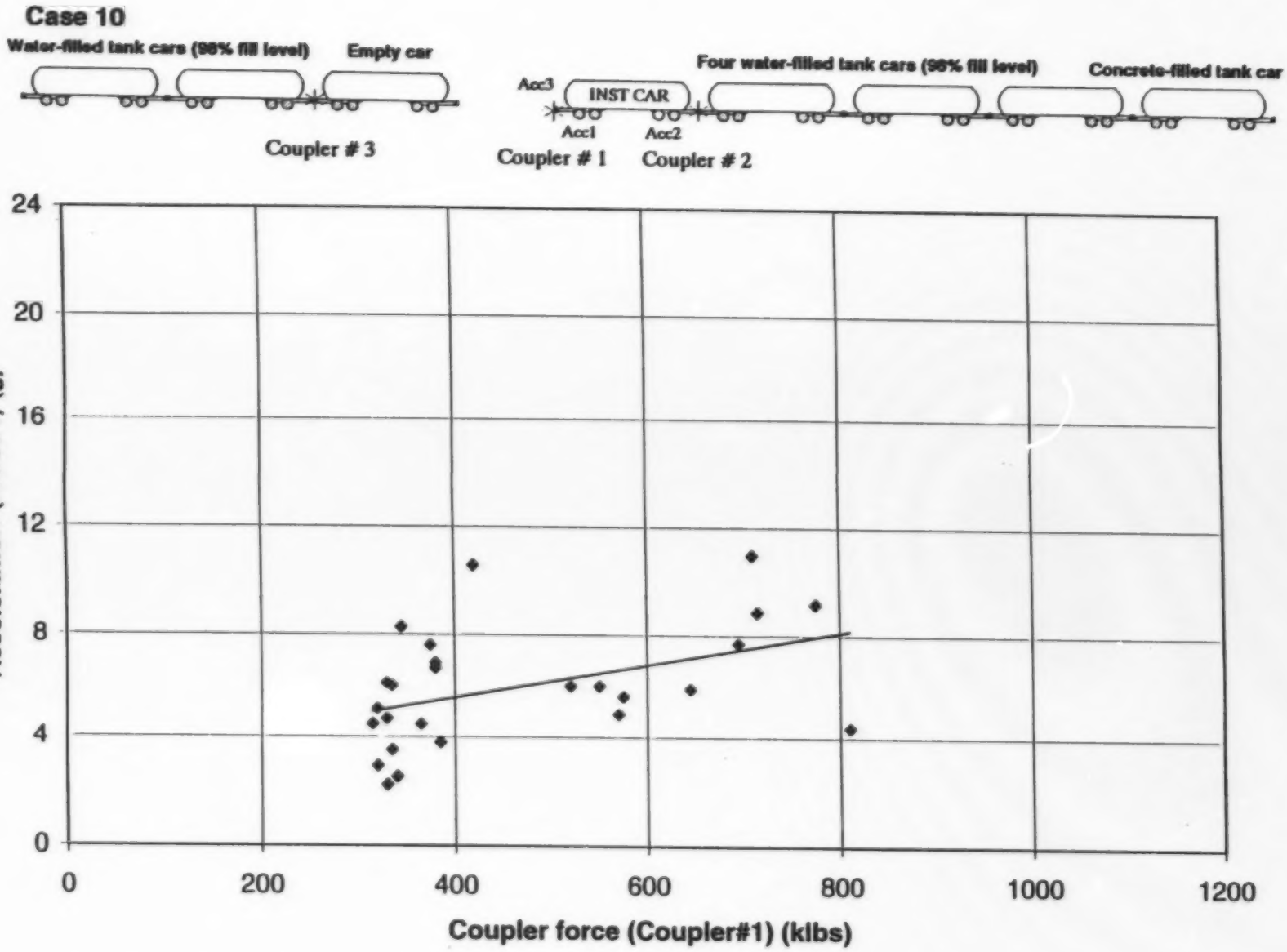


Figure 32. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 10

Case 11

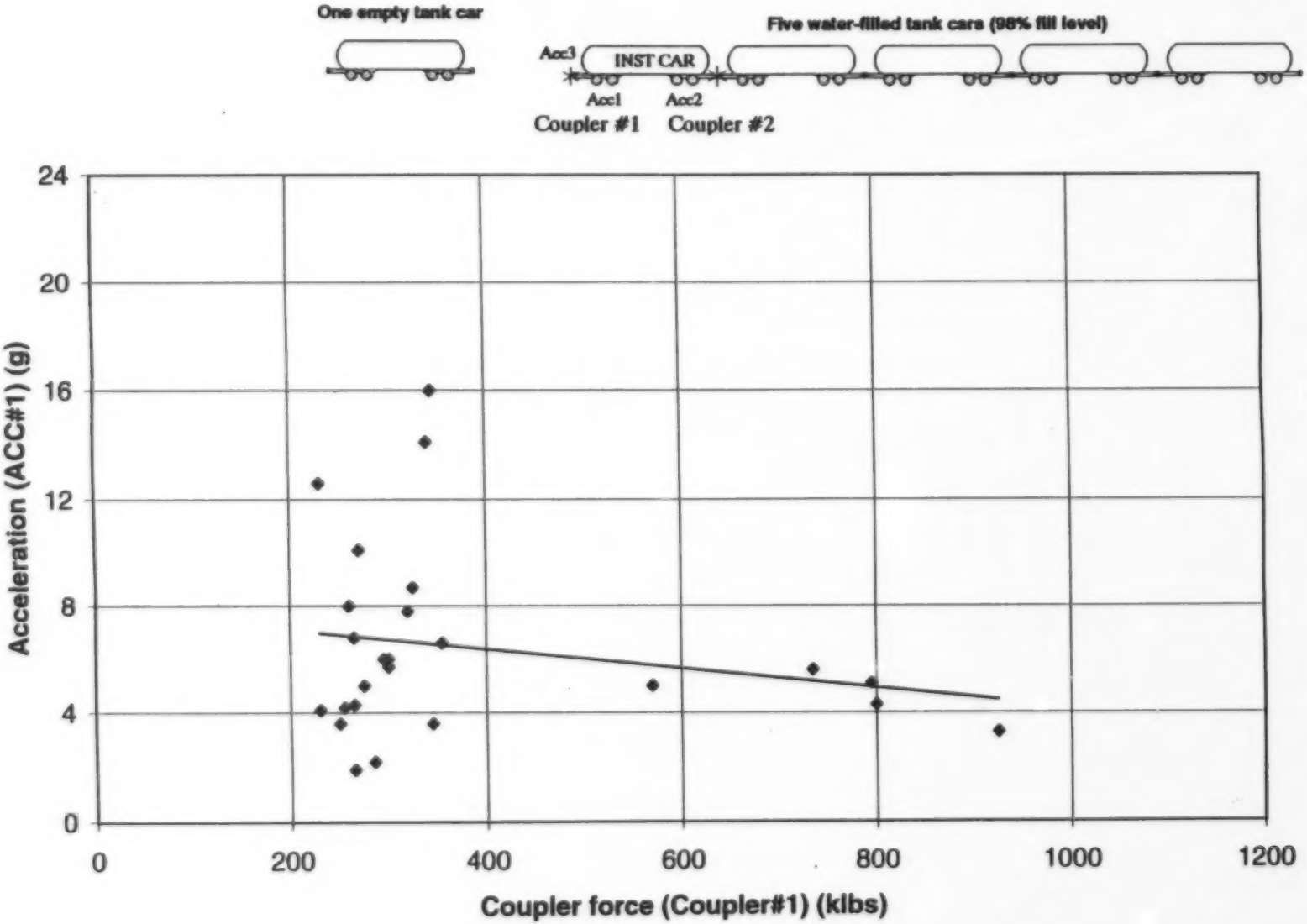
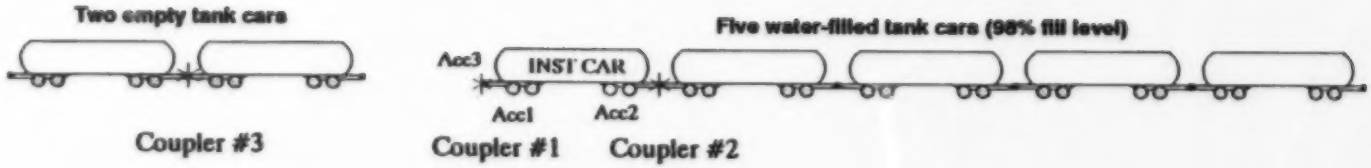


Figure 33. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 11

Case 12



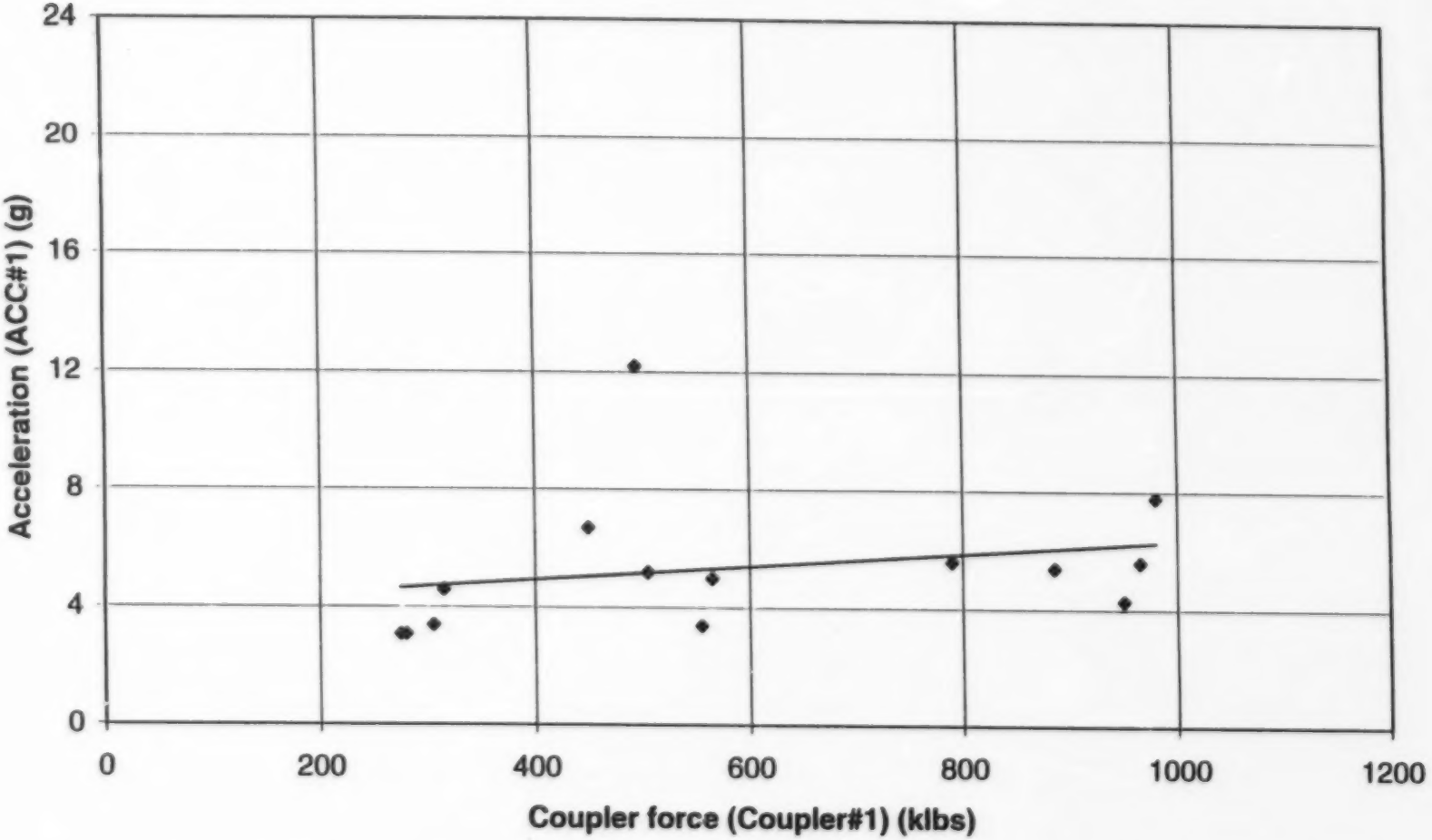


Figure 34. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 12

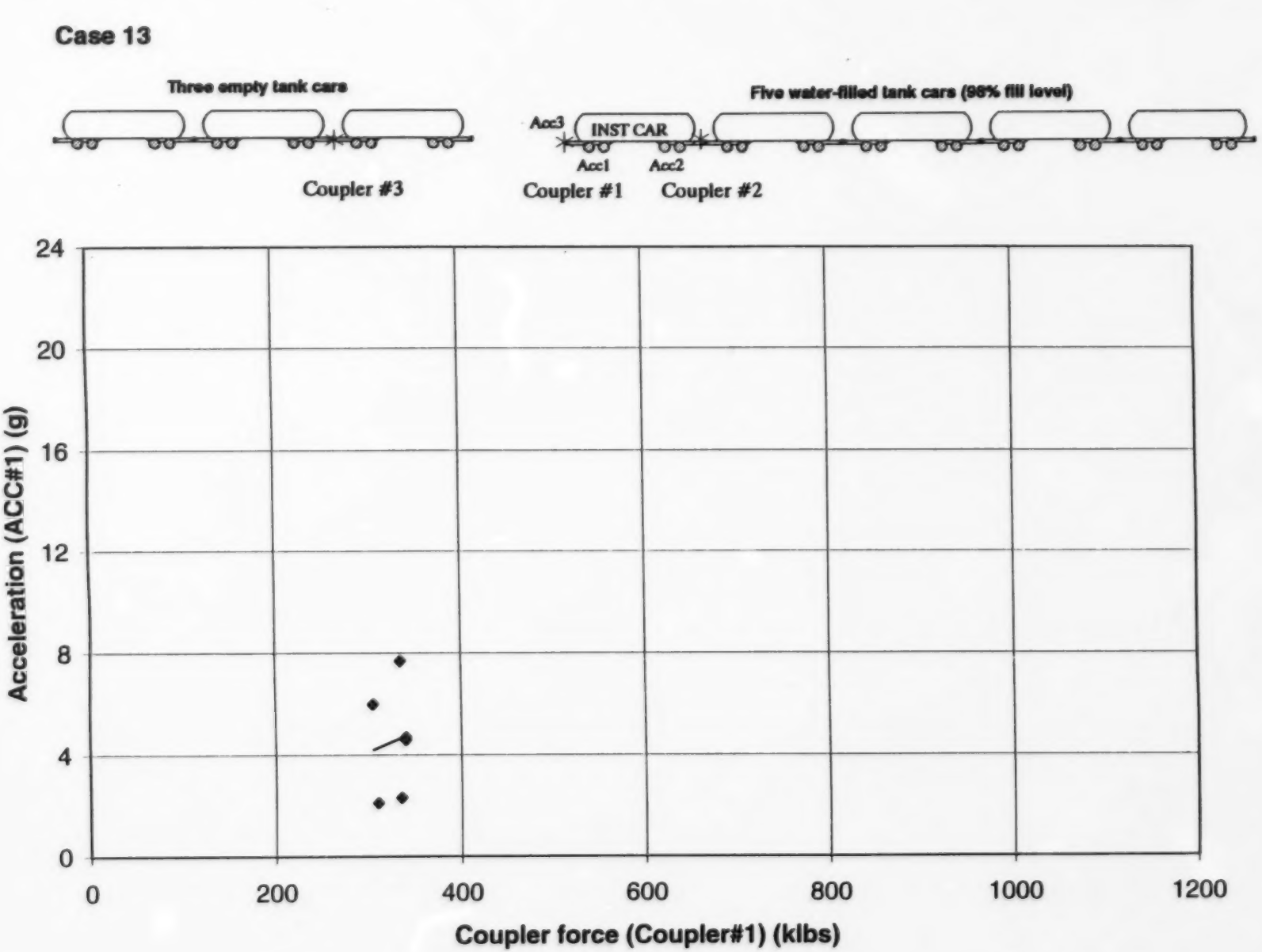
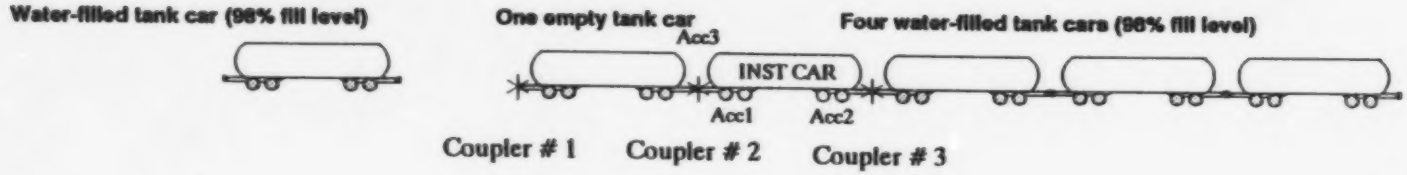


Figure 35. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 13

Case 14



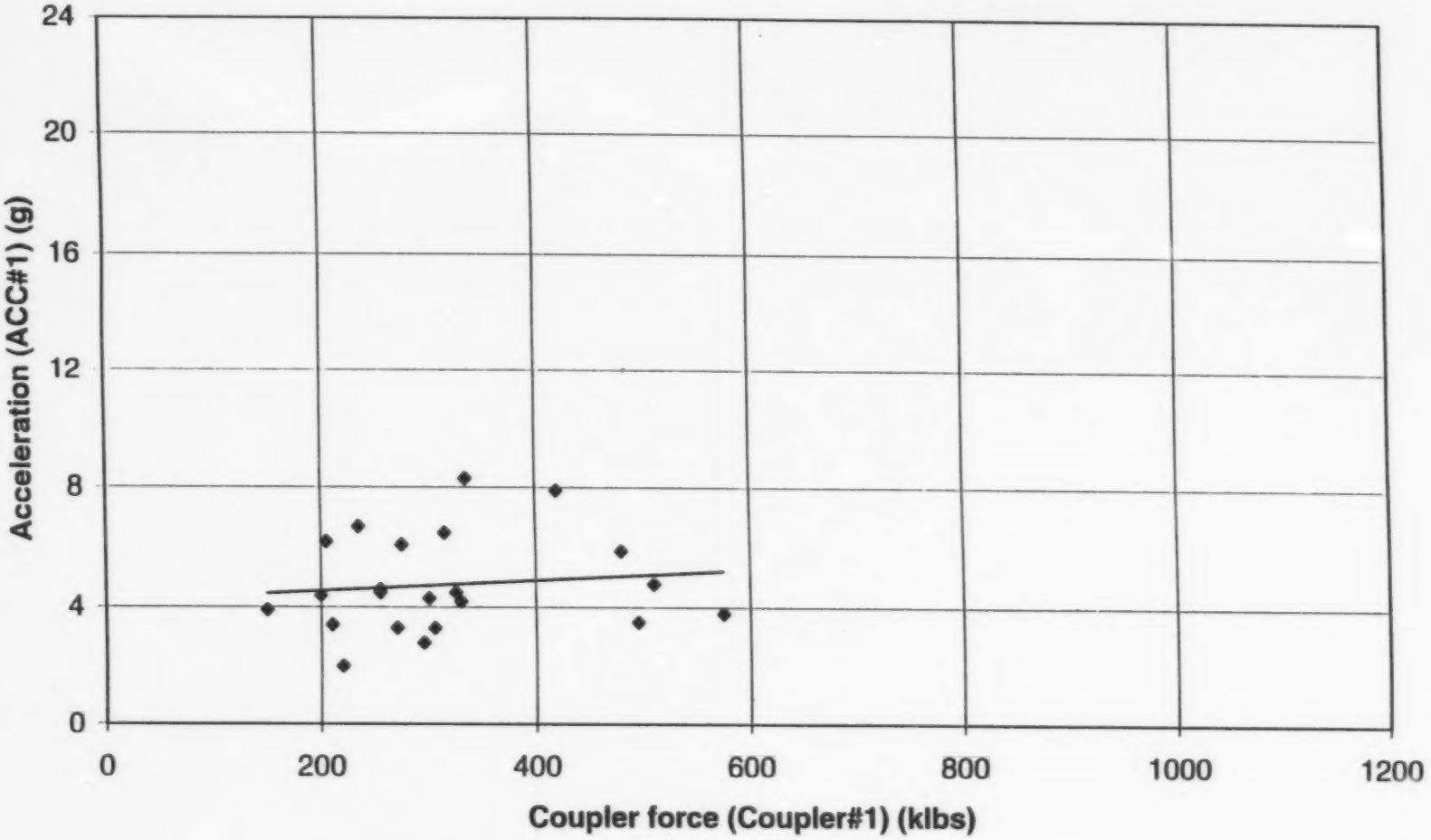
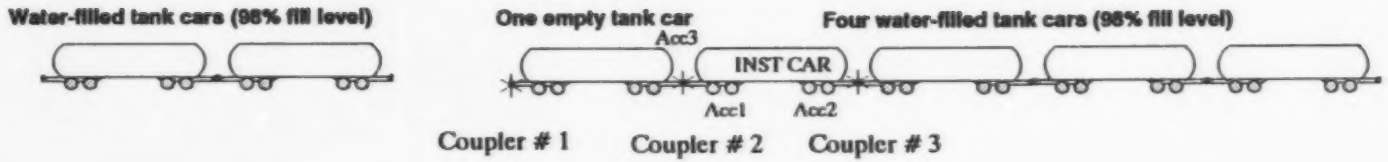


Figure 36. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 14

Case 15



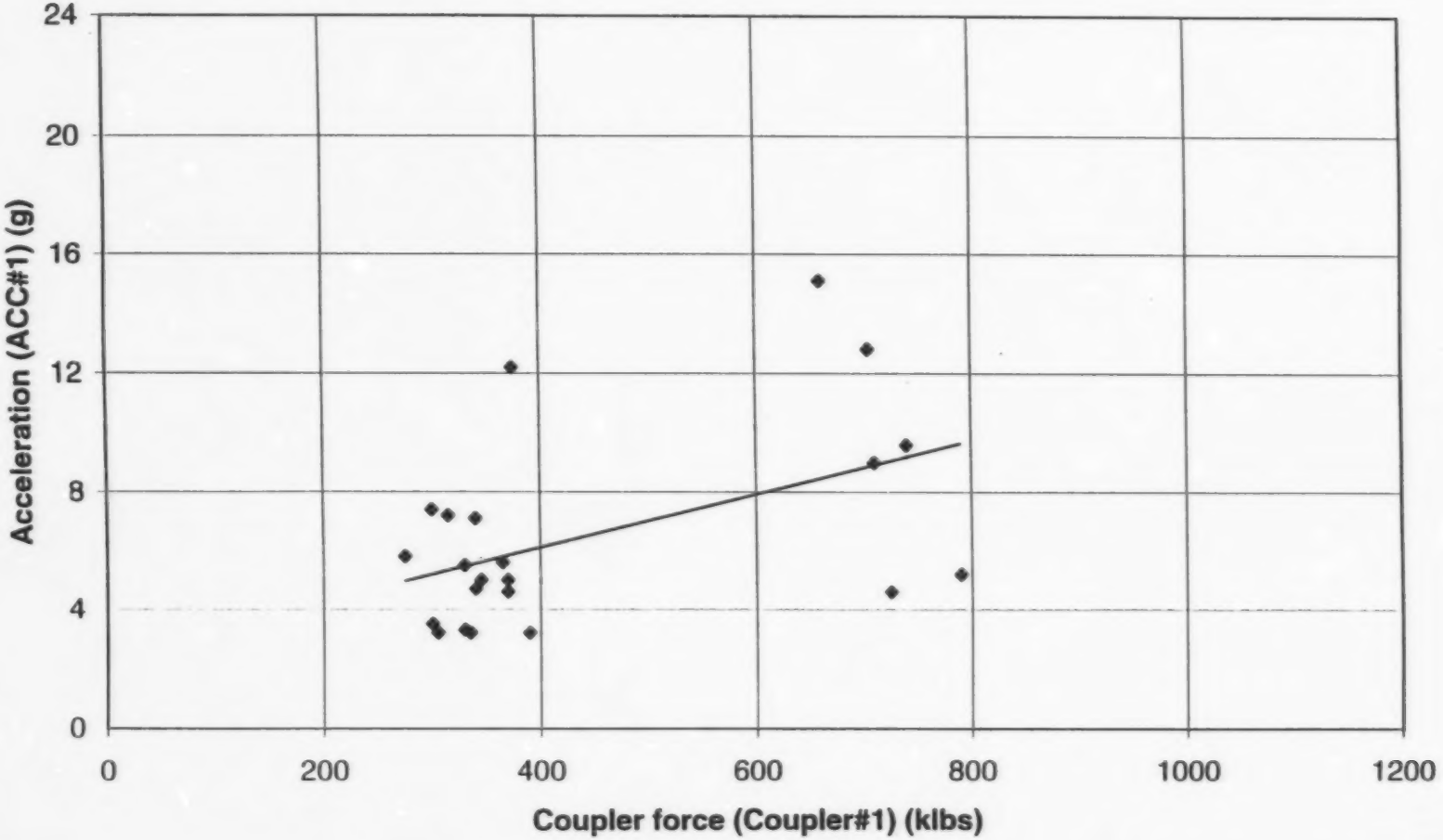


Figure 37. Maximum acceleration (ACC1) versus maximum impact force at coupler # 1 for case # 15

4. CONCLUSIONS

The effects of various factors on tank car impact forces were investigated, using impact tests with 15 different test cases. Some of the findings are summarized in the following conclusions, while others may need further verification from the impact model simulation.

- The maximum impact force at the striking end generally increases with the impact speed exponentially. Controlling the impact speed is the most effective way of limiting the impact force and protecting the tank car structure from damage.

- The maximum impact force from a single hammer car is always lower than that from a multi-car impact at a given speed. A similar phenomenon was observed during testing when a different number of anvil cars was used. However, the maximum impact force increases only marginally when the number of hammer cars increases from two to three. A similar phenomenon was observed when different number of anvil cars was used. Based on these observation, it is predicted that the maximum impact force measured using three cars should not be significantly different from that using more than three cars.

- At the same impact speed, empty cars always generate a lower impact force than loaded cars.

- The maximum impact force generally occurred at the striking coupler. Even when the first hammer car or the first anvil car was empty, the impact forces on the couplers next to the striking coupler were generally lower than those at the striking coupler. This phenomenon needs further investigation during the model simulation.

- The impact forces generated on the hammer cars would not differ from those on the anvil cars if their conditions were the same.

- The longitudinal accelerations on the tank car generally increase with the impact speed. However, the data are usually very scattered. It may not give an accurate indication of the impact force acting on the car. In other words, it is not as reliable as the impact force measured from the instrumented couplers.

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[1] Militaru, D., "Tank Car Stub Sill Analysis," Centre for Surface Transportation Technology, National Research Council of Canada, Technical Report No. CSTT-RYV-CAT-026, May 1996.

[2] Dong, R., and Militaru, D., "Dynamic Structural Characterization of Stub Sill Tank Cars Utilizing ADAMS and ANSYS Simulation Models," Centre for Surface Transportation Technology, National Research Council of Canada, Technical Report No. CSTT-RYV-TR-010, March 1997.

[3] Sturk, M., Majeed, O., and Nicks, J., "Development of a Tank Container Impact Test Standard," TES Technical Report No. C2174-003, 1998.